NATIONAL RESEARCH COUNCIL

AMERICAN GEOPHYSICAL UNION
TRANSACTIONS OF 1941

PART III

TWENTY-SECOND ANNUAL MEETING
APRIL 30 TO MAY 3, 1941
WASHINGTON, D. C.

REPORTS AND PAPERS
SECTION OF HYDROLOGY

PUBLISHED BY THE NATIONAL RESEARCH COUNCIL
OF
THE NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D. C.
AUGUST, 1941

GENERAL CONTENTS
TRANSACTIONS OF 1941

Page

Part I--Reports and papers, Joint Regional Meeting, Section of Hydrology and Western Interstate Snow-Survey Conference, South Pacific Coast Area, Sacramento, California, January, 1941 1

(A) Reports and papers, Section of Hydrology, January 16 to 18, 1941. 5

(B) Reports and papers, Western Interstate Snow-Survey Conference, January 16, 1941 . 131

Index of authors and subjects, Part I 214

Part II--Transactions, Twenty-Second Annual Meeting, Washington, D. C., April 30 to May 2, 1941 (proceedings of General Assemblies and of all Sections except Section of Hydrology) 217

Introduction. 219

General Assemblies (Presidential address, Third award of William Bowie Medal, and Symposium on dynamics of land-erosion) 223

Reports and papers, Sections of Geodesy, Seismology, Seismology jointly with Eastern Section of Seismological Society of America, Meteorology, Terrestrial Magnetism and Electricity, Oceanography, Volcanology, and Tectonophysics 321

Minutes (General Assembly, all Sections, reports, and appendices) 559

Index of names and subjects, Part II. 579

Part III--Transactions, Twenty-Second Annual Meeting, Washington, D. C., April 30 to May 3, 1941 (proceedings of Section of Hydrology) 585

Introduction. 587

Papers. 589

First session, May 1, 1941 593

Second session, May 1, 1941. 666

Third session, May 2, 1941 788

Reports 899

First session, May 1, 1941 901

Second session, May 1, 1941. 917

Third session, May 2, 1941 953

Fourth session, May 3, 1941. 1027

Index of names, Part III. 1030

Index of subjects, Part III 1032

INTRODUCTION

The American Geophysical Union was established in 1919 as the American Committee of the International Union of Geodesy and Geophysics, and its Executive Committee is the Committee on Geophysics of the National Research Council. The objects of the Union are to promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication. In the accomplishment of these objects, the Union is divided into Sections following the plan of organization of the International Union of Geodesy and Geophysics. There are now eight Sections, namely, (a) Geodesy, (b) Seismology, (c) Meteorology, (d) Terrestrial Magnetism and Electricity, (e) Oceanography, (f) Volcanology, (g) Hydrology, and (h) Tectonophysics. A Section of Geophysical Chemistry was discontinued May 31, 1924, as the International Union had failed to provide such a Section. The Section of Hydrology was established November 15, 1930--matters pertaining to scientific hydrology referred to the American Geophysical Union had been previously looked after by special committees on Hydrology. The Section of Tectonophysics was established April 9, 1940, for the purpose of promoting and encouraging research of fundamental importance to our knowledge of Earth-structure not covered in any one of the other Sections of the Union.

The annual assemblies of the Union and annual meetings of its Sections for the discussion of reports and symposia are held each year. [For a summarized statement regarding these meetings and the publications covering them, and for the regional meetings and joint meetings of the Union, see "Transactions of 1941" (Part II, p. 219, and Part I, p. 3, 1941).]

Part I [pp. 1-216] of the "Transactions of 1941" contains the papers and discussions at the Regional Meeting, South Pacific Coast Area of the Section of Hydrology, held jointly with the Western Interstate Snow-Survey Conference, at Sacramento, California, January 16 to 18, 1941. Part II [pp. 217-584] contains the papers and discussions at the Twenty-Second Annual Meetings of the Union and of all of its Sections, except that of Hydrology, held at Washington, D. C., April 30 to May 3, 1941.

The present volume, Part III [pp. 585-1036], is devoted entirely to the papers, reports of Committees, and discussions presented at the four sessions of the Section of Hydrology of the Union held at Washington, D. C., May 1 to 3, 1941. At each of these sessions, as will be noted from the lists of contents [pp. 590-592, and 900], there was very active discussion; it has been possible to include most of these discussions, which make nearly ten per cent of Part III. At the first three sessions there were presented and discussed 40 individual papers and 15 reports with three extensive appendices from the Permanent Research-Committees and other Committees of the Section. The final session on May 3, 1941, was given over to a "Round-table on runoff and infiltration" [pp. 1027-1028].

In addition to the papers published in Part III, attention may be called to the "Symposium on dynamics of land-erosion" held at the General Assembly of the Union on May 2, 1941, which is published in Part II [pp. 236-320] and is of interest to hydrologists. This Symposium was based on six papers, amplified by 13 written discussions.

L. K. Wenzel was in charge of the preliminary editing of the manuscripts of the papers, reports, and discussions, having the assistance of a number of his colleagues in the Section. Final editing and preparation of master-copy for publication were done by Dr. J. A. Fleming and J. J. Capello, General Secretary and Assistant Secretary, respectively, of the American Geophysical Union, and by W. E. Scott and A. D. Singer. We are indebted to W. C. Hendrix for the necessary redrawing of figures and photographic work for publication.

For the excellence of the offset publication of Part III, as also of Parts I and II, we have to thank the Kirby Lithographic Company, Inc., of Washington, D. C.

The great range of subject-matter--theoretical, observational, and practical--at the four sessions of the Section of Hydrology of the American Geophysical Union emphasizes the growth of the scientific and economic aspects of this field of geophysics.

J. A. Fleming, General Secretary,
American Geophysical Union

AMERICAN GEOPHYSICAL UNION

TWENTY-SECOND ANNUAL MEETING

APRIL 30 - MAY 3, 1941

SECTION OF HYDROLOGY

REPORTS

WASHINGTON, D. C.
MAY 1, 2, 3, 1941

CONTENTS

PAPERS

Page

First Session, 9 a.m., May 1, 1941

Criteria for recognition of sea water in ground-waters. ROGER REVELLE. 593

Discussion. A. C. LANE 597

The viscosity of highly concentrated underflows and its influence on mixing. H. A. EINSTEIN. 597

Engineering calculations of suspended sediment. E. W. LANE and A. A. KALINSKE. 603

Some experiments on the transportation of suspended load. VITO A. VANONI 608

Discussion. W. W. RUBEY, A. A. KALINSKE, and C. S. JARVIS. 620

Rational equation of river-bed profile. SAMUEL SHULITS 622

Discussion. W. W. RUBEY and SAMUEL SHULITS 630

Basic aspects of stream-meanders. GERARD H. MATTHES. 632

Discussion. GEORGE W. HOWARD 636

Channel-storage and discharge-relations in the lower Ohio River Valley. B. R. GILCREST and L. E. MARSH 637

A consideration of factors influencing reservoir-sedimentation in the Ohio Valley Region. G. M. BRUNE and R. E. ALLEN 649

The heat-balance method for the determination of evaporation from water-surfaces. BENJAMIN HOLZMAN. 655

Discussion. HERBERT C. S. THOM 659

Interception of rainfall by mature lodgepole-pine. H. G. WILM and C. H. NIEDERHOF. . . . 660

Second Session, 2 p.m., May 1, 1941

Application of the infiltration-theory to engineering practice. L. K. SHERMAN and L. C. MAYER 666

Methods for the measurement of infiltration. H. G. WILM. 678

Factors influencing infiltration-rates into some California soils. MARTIN R. HUBERTY and ARTHUR F. PILLSBURY 686

Discussion. N. E. EDLEFSEN, ROBERT E. HORTON, and L. K. SHERMAN. 694

Considerations on an index to measure effective rainfall. JOSÉ GARCIA MONTES 697

Long-term constancy of rainfall. CARROLL F. MERRIAM. 703

Discussion. CARROLL F. MERRIAM and HERBERT C. S. THOM. 707

Measurements of the fall-velocity of water-drops and raindrops. J. OTIS LAWS 709

Discussion. G. W. MUSGRAVE 721

Extending the forecasts of temperature for the prediction of stream-flow from snow-melt. R. K. LINSLEY 722

Hydrometeorology of the San Juan River Basin, Mexico. ANDRÉS GARCÍA QUINTERO 726

PAPERS—CONTINUED

Page

Second Session--Concluded

The effect of a well on the flow of a nearby stream. C. V. THEIS 734

Discussion. L. K. WENZEL 737

Ground-water inventory in the upper Gila River Valley, New Mexico and Arizona: Scope of investigation and methods used. S. F. TURNER and L. C. HALPENNY. 738

Coefficients of storage and transmissibility obtained from pumping tests in the Houston District, Texas. C. E. JACOB 744

Application of coefficients of transmissibility and storage to regional problems in the Houston District, Texas. W. F. GUYTON. 756

Discussion on the two preceding papers. M. KING HUBBERT. 770

Factors producing a nine-year decline in ground-water levels in Scott County, Kansas. HERBERT A. WAITE. 772

Ground-water dams created by faulting of alluvial sediments in the Hurricane Fault-Zone, Utah. H. E. THOMAS 775

Depth of active solution by ground-waters in the Pecos Valley, New Mexico. ARTHUR M. MORGAN. 779

Discussion. A. C. SWINNERTON 783

Notes on the elasticity of the Lloyd sand on Long Island, New York. C. E. JACOB. 783

Third Session, 9 a.m., May 2, 1941

U. S. Coast Guard Cutter Northland's ice and oceanographic observation cruise, Baffin Bay and Davis Strait, autumn of 1940. ED. H. SMITH 788

Discussion. MAX DEMOREST 791

Ice-crusts and snow-settling, Snoqualmie Pass, winter of 1940-1941. PHIL E. CHURCH . . . 793

Discussion. C. H. DIEBOLD. 795

A gazetteer of Alaskan glaciers. WM. O. FIELD, JR. 796

A proposed method for calculating stream-flow. O. E. GUTHE 799

Discussion. F. F. SNYDER and G. W. MUSGRAVE. 808

Virtual channel-inflow graphs. ROBERT E. HORTON. 811

Flood-crest reduction by channel-storage. ROBERT E. HORTON 820

Probability-interpretation of the observed return-periods of floods. E. J. GUMBEL. . . . 836

Discussion. RALPH W. POWELL and E. J. GUMBEL 849

Period versus instantaneous distribution-coefficients. WALDO E. SMITH. 851

Discussion. WILLIAM T. COLLINS 854

Runoff from terraced areas under conditions of extreme flood. DAVID W. CARDWELL and W. E. DICKERSON, JR. 856

Limitations of the duration-interval concept of flood-recurrence intervals. R. S. GOODRIDGE 862

PAPERS—CONCLUDED

Page

Third Session--Concluded

Separating storm-hydrographs from small drainage-areas into surface- and subsurface-flow C. R. HURSH and E. F. BRATER. 863

Discussion. W. G. HOYT 870

Preliminary results of runoff-studies at Fennimore, Wisconsin, show low rates and amounts of runoff. N. E. MINSHALL. 871

Estimating annual yield from ungaged drainage-basins and effect of land-use treatment on surface-runoff. C. S. JARVIS and H. C. MURTO 875

A graphical flood-routing method. WALTER T. WILSON 893

Discussion. W. B. LANGBEIN 897

Index of names, Part III. 1030

Index of subjects, Part III 1032

PAPERS, SECTION OF HYDROLOGY

NATIONAL ACADEMY - RESEARCH COUNCIL BUILDING
FIRST SESSION, 9:00 A.M., MAY 1, 1941

CRITERIA FOR RECOGNITION OF SEA WATER IN GROUND-WATERS

Roger Revelle

(Contribution from the Scripps Institution of Oceanography, New Series, No. 144)

In semiarid regions near the seacoast excessive pumping of wells is liable to cause salt-water intrusion either from the ocean itself or from relatively impervious marine sedimentary rocks surrounding the aquifer which yields ground-water. Since the ground-waters of semiarid regions commonly have a relatively high and variable concentration of dissolved salts, a slight increase in concentration, such as is found by measuring resistivity [see 6 of "References" at end of paper], may not alone be sufficient to prove the presence of sea water. On the other hand, since ground-waters usually differ widely from sea water in composition, it might be thought that changes in the proportions of different chemical components of well-waters in the direction of sea water could be used to detect the beginnings of admixture. Actually, however, the observed changes in composition of well-waters may be quite different from those that would occur on simple mixing with a small portion of sea water owing to the modifications which sea water itself may undergo as it passes through the ground or through marine and estuarine sediments. The absence of those proportional changes which would result from a direct mixture of sea water and ground-water cannot be taken as a warrant for disregarding other signs of salt-water encroachment.

The modifications in composition which sea water can undergo on passing through soil or sediment may be divided for convenience into three categories: Those which affect the proportions between positively charged ions (cations) alone; those which affect only the proportions between negatively charged ions (anions); and those which result in changes of equal significance among both cations and anions. In the first class are modifications resulting from base exchange between the water and the minerals of soil or sediment, in the second category are changes in sulphate and bicarbonate content due to processes of sulphate reduction and substitution of carbonic or other weak acid radicals, and processes of solution and precipitation which affect the relative amounts of both positive and negative ions make up the third group. Only solution and precipitation result in gain or loss of total salts considered as concentration values. In processes of base exchange, oxidation-reduction, or acid replacement, the total equivalent amount of bases and acid radicals remains unchanged, because ionic balance must be preserved. The percentage by weight of different salt components is altered, however, and the total dissolved solids in part per million may be increased or decreased.

Alteration of sea water by base exchange--Although the total amount of hydrogen, sodium, potassium, calcium, and magnesium in any given clay or soil is roughly constant, the proportions between these various bases differ widely, depending on the composition of the water with which the soil is in contact. The bases that can be interchanged between the water and the soil are called replaceable bases. Kelley and Liebig [3] found that if a soil is repeatedly leached with a solution containing several cations, such as sea water, a state of equilibrium is finally attained, that is, when the soil is placed in contact with a new portion of the solution neither the soil nor the water gains or loses any cations whatever. It is known also that base-exchange reactions take place rapidly, and it therefore seems reasonable to conclude that when any soil or sediment containing clay, organic matter, or other base-exchange material is placed in contact with water containing dissolved salts, an equilibrium partition of the various bases present between the water and the soil is quickly reached. It might be expected that at equilibrium the bases would be present in the same proportions in both the water and the soil, but this is not the case. The cations differ widely in "base-exchange activity," that is, in their tendency to replace each other on and within the crystal lattices of clays or other base-exchange minerals. Among other things, the base-exchange activity of a cation depends on the size and degree of hydration of the ion, and to some extent, also, on the character of the minerals involved in the reaction. In general, calcium, potassium, and magnesium have a far higher base-exchange activity than sodium. For example, the percentage of replaceable magnesium exceeds that of sodium in a clay in equilibrium with sea water, even though the equivalent amount or reacting value of sodium in ocean water is over four times as great as the reacting value for magnesium. Soils in which sodium makes up more than 60 per cent of the replaceable bases can only be obtained by leaching with an almost pure sodium solution [2].

For any given initial composition of water and sediment it should be possible to predict the approximate equilibrium composition of the water and the proportions between the exchangeable bases present in the sediment. This may be done by utilizing the principle of mass-equilibrium as it applies, for example, to the partition of a mixture of gases between a liquid solvent and the gas-phase in contact with it. Just as the ratio between any two gases in the solvent is in direct proportion to the ratio in the gas-phase multiplied by the ratio of the solubilities of the two gases, so the proportion of any two bases in the soil colloid should bear a constant ratio to the proportions in the water multiplied by the ratio of the base-exchange activities of the two bases. That is, if we take sodium and calcium as examples:

$$(\text{Pct } Ca_{soil}/\text{pct } Na_{soil}) = (K_{Ca}/K_{Na})\ (\text{pct } Ca_{water}/\text{pct } Na_{water})$$

where the terms K_{Ca} and K_{Na} may be taken to represent the coefficients of base-exchange activity of calcium and sodium, respectively, and the terms pct Ca_{soil}, pct Ca_{water}, etc., refer to percentage of total replaceable bases in the soil or the total bases in the water, considered as equivalents. To a first approximation, at least, this relation will hold, regardless of the absolute concentration of the solution, the base-exchange capacity of the soil, or the relative amounts of other cations.

It is not possible to arrive at absolute values of the base-exchange activity coefficients of individual cations. Approximate ratios between the activities of any two major ions may be calculated, however, from the data given by Kelley and Liebig [3] for the average percentages of the replaceable bases in two clays in equilibrium with sea water. These data are shown in Table 1, together with the calculated ratios between activities.

Table 1--Approximate ratios between activities of major ions

Item	Percentages of total replaceable cations			
	Ca	Mg	Na	K
Sea water (Lyman and Fleming [4])	3.4	17.6	77.4	1.6
Average of two clays in equilibrium with sea water (Kelley and Liebig [3])	15.3	41.5	36.6	6.6
Ratios of base-exchange activities, referred to sodium, that is, (K_{Ca}/K_{Na}), (K_{Mg}/K_{Na}), (K_K/K_{Na})	9.5	5.0		8.7

Because of the paucity of observations and the variability in behavior of different base-exchange materials, little reliance can be placed on the actual numerical values for the activity ratios. They merely serve to emphasize the fact that sodium has from five to ten times as great a tendency as either calcium, magnesium, or potassium to remain or enter in solution at the expense of the other bases when in contact with base-exchange materials.

Where the proportions between calcium, potassium, and magnesium are relatively constant, the percentages of sodium in the soil and in the water have the relationship indicated by the following equation.

$$\left(\frac{\text{pct } Na_{soil}}{100 - \text{pct } Na_{soil}}\right) = \left(\frac{K \times \text{pct } Na_{water}}{100 - \text{pct } Na_{water}}\right)$$

in which K is a constant. This equation may be transformed algebraically to give

$$\left(\frac{1}{\text{pct } Na_{water}}\right) = \left(\frac{K}{\text{pct } Na_{soil}} + \frac{1}{100} - \frac{K}{100}\right)$$

From Table 1 it may be calculated that K for sodium varies between 0.1 and 0.2. In sea water and all other solutions having the same proportions between calcium, magnesium, and potassium, K = 0.168. Exactly analogous relationships exist between the proportions of other bases in sediments and interstitial waters, except that for calcium, magnesium, and potassium, K is considerably greater than one. The percentage of replaceable sodium which may be present in a sediment or soil in equilibrium with any given percentage of sodium in an interstitial water solution in which K = 0.168 is shown in Figure 1. Whenever the initial percentage of replaceable sodium in the sediment is higher than the equilibrium value (about 37 per cent for sea water), the solution will gain in sodium and lose other bases; when the sediment originally contains less than the equilibrium proportion of replaceable sodium, the water will lose sodium and acquire other bases in equivalent quantity. The extent of the changes undergone, respectively, by the water and the sediment will depend on the relative quantity and replaceable base-content of the sediment as compared with the concentration and quantity of the water. When a small amount of sea water or other solution enters an aquifer, the equilibrium proportion of bases in the water will be virtually the same as that of the ground-water previously present there. On the other hand, a large quantity of water will bring the sediment into equilibrium without itself appreciably changing in composition, while when approximately equal amounts of water and sediment or soil are present there will occur profound changes both in the replaceable bases of the sediment and in the proportions of the different cations in the water.

Fine-grained soils of semiarid regions may contain from 5 to 40 or more milliequivalents of replaceable bases per 100 grams, depending on the content of colloidal material and the character of the clay minerals present. Undiluted sea water contains about 59 milliequivalents of bases per 100 grams, an amount of only slightly greater magnitude, when it is considered that usually less than a third of a soil-water mixture will be water. A permeable underground water-bearing stratum may contain smaller quantities of replaceable bases per unit-weight than the overlying soils, but enough colloidal material will usually be present to allow for major alterations in a solution newly entering the stratum and replacing the water previously present therein.

When the base-exchange capacity and amount of soil, the amount of water, and the total amount of each base involved in a base-exchange reaction are known, it is possible by means of simultaneous equations to calculate the final concentration at equilibrium of all cations in the water and the proportions between the bases in the soil. These complete data are seldom if ever available, however, in considering problems of salt-water intrusion. Neither the route followed by the water nor the quantity and character of the sediments through which it has passed can be known with certainty. Consequently, changes in the ratios between different bases observed in well water cannot usually be used as valid criteria of the presence of sea water, nor can the absence of such changes be taken as evidence that sea-water contamination has not occurred. The ratio between sodium and magnesium may under certain circumstances prove useful in detecting the presence of "fossil" sea-water derived from ancient marine sediments, as analyses by Case and others [1] indicate that at least in oil-field waters magnesium is very low compared with sodium. This is probably owing to a change of state of the magnesium in the sedimentary clays in contact with the water from a replaceable to a non-replaceable form during the long years since these sediments were first laid down by the sea.

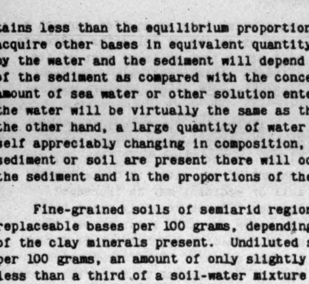


Fig. 1--Equilibrium-percentages of sodium in soil and interstitial water (arrows indicate modifications that will occur when water of different composition is placed in contact with the soil)

Alteration due to sulphate reduction--Oil-field waters, which are usually considered to be fossil sea-water trapped in marine sedimentary rocks, often have little or no sulphate, in contrast to sea water in which the amount of sulphate by weight is about one-seventh of the chloride. Likewise, the interstitial waters of recent marine and estuarine sediments have been observed by Murray and Irvine [5] and by Rittenberg and Revelle [9] to be often extremely low in sulphate. The first-named workers found that in the waters investigated by them the amount of sulphate lost was just balanced by a gain of "titratable alkalinity," that is, essentially in bicarbonate content. These alterations in the composition of sea water in contact with sediments containing organic matter were shown to result from the bacterial reduction of sulphate ion to hydrogen sulphide, and the concomitant oxidation of some of the organic matter to carbon dioxide, as indicated in the following schematic equation.

$$3\ Na_2SO_4 + C_6H_{12}O_6 \xrightarrow{\text{bacteria}} 3\ H_2S + 6\ NaHCO_3$$

where it is assumed for simplicity that the organic matter oxidized is entirely glucose.

Since sulphate reduction can and probably does take place wherever anaerobic conditions exist and there is a supply of oxidizable organic matter, it should be expected that sea water

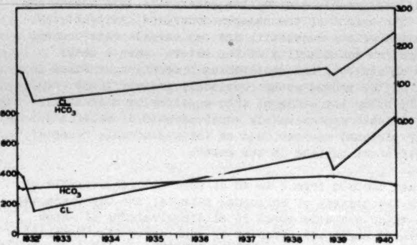


Fig. 2--Increase in (Cl/HCO_3)-ratio in a well near Oceanside, California

penetrating into an aquifer through a layer of marine or estuarine sediments will often lose at least part of its sulphate content and gain a corresponding amount of bicarbonate ion.

Alteration due to solution and precipitation--Under certain conditions, on the other hand, the sulphate content of sea water in contact with soil or sediment may be increased. Posnjak [7] has recently shown that sea water can hold about three times as much calcium sulphate as it actually does contain. Thus, ocean water in contact with gypsum or anhydrite, both common constituents of certain sediments, will gain as much as 75 per cent of its initial sulphate content and at the same time the calcium content will be tripled. If the pH is about 8, calcium carbonate will then be precipitated and still more sulphate may be dissolved. The precipitation of calcium carbonate may also accompany the process of sulphate reduction, particularly if this process takes place under sufficiently alkaline conditions, so that part of the bicarbonate produced is converted to carbonate ion. The actual solubility product of calcium carbonate in sea water is not accurately known, but it is generally agreed that at a pH of 8 or above and at temperatures greater than 20° C, normal sea water is saturated with calcium carbonate [11, 8] and that consequently an increase in either calcium or bicarbonate ion will tend to bring about precipitation.

Of all the major ions occurring in sea water only chloride is unaffected by the processes of modification which have been described. Chloride is the dominant ion of ocean water and usually plays only a minor role in ground-waters; hence an increase in chloride content is the most reliable indicator of the first stages of salt-water intrusion into ground-water. A small rise in chloride may, however, be due simply to a temporary increase in the total concentration of dissolved salts and thus may be of no diagnostic significance. It is necessary to eliminate the effects of changes in concentration by introducing a ratio between chloride and one or more of the other ions in solution. For this purpose the ratio between chloride and bicarbonate (or total bound carbon dioxide) immediately suggests itself. Bicarbonate is usually the most abundant negative ion in ground-waters, while bicarbonate and carbonate taken together are present in virtually negligible amounts in sea water, the weight ratio of chloride to bicarbonate being about 190 to 1. Even though, as has been pointed out, the bicarbonate content may be altered somewhat by the precipitation of calcium carbonate or by the oxidation of organic matter which accompanies sulphate reduction, there is such a large difference between the proportions of chloride and bicarbonate in normal ground-water and in ocean water that the ratio between these two ions is a useful index of the presence of sea water. A more serious difficulty is the fact that other processes besides salt-water admixture can bring about a rise in the chloride-bicarbonate ratio of ground-waters. The comparative analyses given by Stabler [10] of desert lakes and of the rivers which flow into them show that repeated evaporation and precipitation tend to raise the chloride-bicarbonate ratio, and indeed cause the composition of the lake-waters to change in many respect in the direction of sea water. Contamination by sewage and industrial waters or by any relatively salty water of whatever origin will also cause an increase in chloride at the expense of bicarbonate. When an increase in the ratio between these ions takes place in wells pumping from the bottom of an aquifer, however, where neither contamination with saline wastes nor evaporation and precipitation are likely factors, then admixture of either recent or fossil sea-water may be inferred with some confidence.

Figure 2 shows the observed changes in chloride and bicarbonate content and in chloride-bicarbonate ratio during the eight-year period from 1932 to 1940 in one of the municipal wells of the city of Oceanside, California. The well was abandoned in 1940. Whether the very evident salt-water contamination shown in this well is due to admixture of recent or of fossil sea-water is not known with certainty. Whatever the source of the salt water, if the warning given by the increase in the ratio of chloride to bicarbonate had been heeded and pumping had been carried on less intensively, the usefulness of the well might have been increased.

References

[1] L. C. Case, Subsurface water characteristics in Oklahoma and Kansas, in Problems of petroleum geology, Bull. Amer. Assoc. Petr. Geol., pp. 855-868, 1934.

[2] W. P. Kelley and S. M. Brown, Principles governing the reclamation of alkali soils, Hilgardia, v. 8, pp. 149-177, 1934.

[3] W. P. Kelley and G. F. Liebig, Jr., Base exchange in relation to composition of clay with special reference to effect of sea water, Bull. Amer. Assoc. Petr. Geol., v. 18, pp. 358-367, 1934.

[4] John Lyman and R. H. Fleming, Composition of sea water, J. Mar. Res., v. 3, pp. 134-146, 1940.

[5] J. Murray and R. Irvine, On the chemical changes which take place in the composition of the sea water associated with blue muds on the floor of the ocean, Trans. R. Soc. Edinburgh, v. 37, pp. 481-507, 1893.

[6] J. F. Poland and R. B. Morrison, An electrical resistivity-apparatus for testing well-waters, Trans. Amer. Geophys. Union, Part I, pp. 35-46, 1940.

[7] E. Posnjak, Deposition of calcium sulfate from sea water, Amer. J. Sci., v. 238, pp. 559-568, 1940.

[8] Roger Revelle, Physico-chemical factors affecting the solubility of calcium carbonate in sea water, J. Sed. Petr., v. 4, pp. 103-110, 1934.

[9] Sydney Rittenberg and Roger Revelle, Sulphate and sulphide in recent marine sediments (in press).

[10] Herman Stabler, Some stream waters of the western United States, U. S. Geol. Surv., W.-S. Paper 274, 188 pp., 1911.

[11] H. Wattenberg, Kohlensaure und Kalzium Karbonat im Meere, Fortschritte Mineral. Kristal. Petrographie, Bd. 20, pp. 168-195, 1936.

Scripps Institution of Oceanography,
University of California,
La Jolla, California

DISCUSSION

A. C. LANE (Cambridge, Massachusetts)--I entirely agree that the problem is often an individual one, and would call attention to the help that may be given by petrographs on the chemical analysis of rocks. As I pointed out in my paper on calcium-chloride waters [comments and diagram in Bull. Amer. Assoc. Petr. Geol.], manganese is one of the most easily precipitated of bases and green chloritic secondary minerals are wide-spread. The problem of waters in Florida, whether from sea water or connate with the anhydrite deposits, is an illustration.

THE VISCOSITY OF HIGHLY CONCENTRATED UNDERFLOWS AND ITS INFLUENCE ON MIXING

H. A. Einstein

The viscosity of a clay suspension is measured for varying degrees of concentration and flocculation and the results interpreted as a possible explanation of the behavior of underflows of water, with high clay concentration, through reservoirs.

Introduction--When we attempt to explain, why, and under what conditions non-mixing underflows are possible, we must remember that an underflow is a problem of hydrodynamics, like any other flow. We must also remember that, from the standpoint of hydrodynamics, laminar flow is the normal kind of flow in a liquid and that laminar flow will take place everywhere unless it is disturbed. These disturbances are called turbulence and are created mainly along solid walls or in places with a discontinuity of velocity. Both kinds of sources for the creation of turbulence are found in the case of an underflow, the solid surface at the bottom, and the discontinuity at the interface between lake water and underflow.

The creation of turbulence is only possible in places where a layer of the fluid is not stable under the influence of the flow. We check this stability by superimposing oscillations of small amplitude on the main flow. If this oscillation has the tendency to grow under the influence of the flow, the flow is not stable and therefore has the tendency to become turbulent. If the disturbance has the tendency to decrease, the flow is stable. From this it is clear that stability of the flow in one place does not prevent the flow from being disturbed by turbulence created in other places. It only states that such disturbances are not increased at a point and no new disturbances are created.

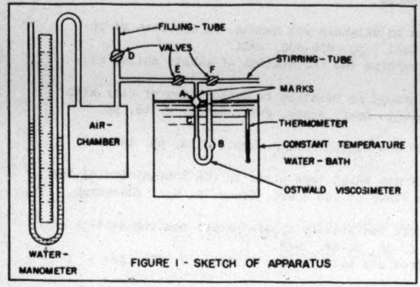


FIGURE 1 - SKETCH OF APPARATUS

Recent investigations on underflow conducted at the National Bureau of Standards [see 6 of "References" at end of paper] have resulted in the derivation of a criterion θ for the stability of the interface of an underflow. It may be emphasized that this criterion only covers the stability of the interface itself, but not the stability of the liquid on either side, which may become turbulent if the underflow is sufficiently long.

In most published experiments on density-currents in small flumes, the Reynolds number of the flow is nearly that of, or even less than, the critical value, and therefore no turbulence is created along the solid walls, especially along the bed. The underflows in Lake Mead, Elephant Butte Reservoir, and similar reservoirs seem to have a Reynolds number of 100,000 and higher and consequently must be considered to be highly turbulent. Therefore, not only the interface between the two layers must be stable according to the θ-criterion, but also the turbulence created along the bed must be prevented from penetrating this interface if no mixing is to occur. The results of a brief investigation of the viscous properties of clay suspensions will suggest an explanation for the fact that even violent turbulence is not able to reach the interface from the bed if the depth and the concentration of the underflow are sufficiently high and, especially, if the sediment is flocculated.

It is to be noted that underflows of high clay concentration are only one phase of the problem of density-currents. The currents may be due not only to suspended matter, with or without flocculation, but also to dissolved matter and temperature, or any combination of these factors. The problem discussed below, however, only pertains to underflows of high clay concentration.

Description of the experiment--An Ostwald water-viscosimeter having a 90-mm capillary tube with 0.4-mm bore was used in the experiments. Since this simple instrument usually operates at constant head, the arrangement shown in Figure 1 was necessary to permit operation with varying heads.

The capillary side of the viscosimeter was connected to an air-pressure system consisting of an air-container and a manometer. The suspension sample under investigation was placed in the U-tube of the instrument. Before each run, the system was brought to the desired pressure by blowing through the fill-tube operating valve D, while valves E and F were closed. Valve F was then opened and the sample thoroughly stirred in the lower part of the viscosimeter, by alternately blowing and sucking through the stirring tube. By further sucking through the stirring tube, the sample was brought into working position by the filling of bulb A. After the closing of valve F, the apparatus was ready for a run. The manometer was then read and valve E opened. The time taken for the surface of the liquid to pass from the mark above bulb A to the mark below it was measured by means of a stop-watch. The volume between the

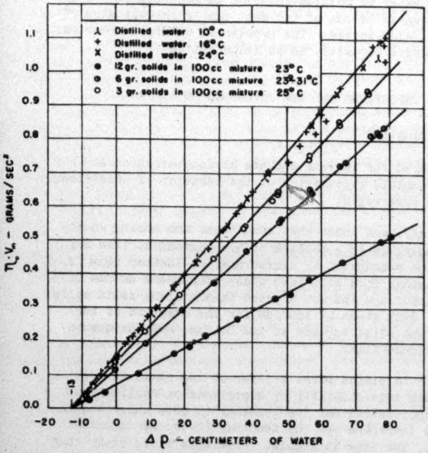


FIGURE 2 - EXPERIMENTS WITH DISTILLED WATER AND DISPERSED SUSPENSIONS

two marks is 1.95 cm. Valve E was closed as soon as the second mark was passed to prevent air from escaping through the instrument. Again the manometer was read, as was the temperature in the water-bath. The measuring time varied from 15 to 1,000 seconds, the temperature from 10° to 30° C, and the pressure from -10 to +80 cm of water.

The sediment used in the experiments was a South Carolina clay, found in a gully where the water at low stages filtered through a bar of fine sand and deposited the clay on the surface of the bar. This clay deposit was collected dry in the field, pulverized in the laboratory, soaked in water, and dispersed by adding sodium oxalate ($Na_2C_2O_4$). A basic mixture was obtained by washing through a 250-mesh sieve and evaporating to a concentration of 12 grams dry-weight solids (excluding dissolved matter) in a 100-cc mixture. A pipette analysis of this basic mixture shows it to be 98 per cent finer than 0.002 mm and 79 per cent finer than 0.0005 mm. Smaller concentrations were obtained by diluting with distilled water and adding more peptizer. Experiments were first made on each sample in the original dispersed state, then with varying degrees of flocculation by gradually adding sodium chloride. When the addition of this salt ceased to increase the viscosity, hydrochloric acid was substituted to further increase it.

Results of the experiments--A preliminary set of experiments was run with distilled water at varying temperatures of from 10° to 24° C. Figure 2 shows the result of these experiments, the main objective of which was to determine the constants of the instrument. These constants are the average internal head of the column and the exact measure of capillarity.

For viscous flow through a tube, the viscosity η is defined by an equation of the form

$$\tau = \eta(\partial v/\partial y) \tag{1}$$

where τ is the shearing stress in the liquid, y is the dimension in the direction of the radius, and v is the velocity. For a particular tube the shearing stress τ in a certain point of the tube is proportional to the total head loss Δp, and $(\partial v/\partial y)$ in a certain point is proportional to the average velocity, v_m, in the tube. Therefore, equation (1) can be rewritten in the form

$$\Delta p \propto \eta \times v_m$$

A plot of ηv_m against Δp therefore must be a straight line, if the flow is laminar. The Reynolds number in any of the tests never exceeded 500, which is below the critical value. For clarification it may be mentioned that the velocity-head, $v_m^2/2g$, must be subtracted from the total head, since no recovery of velocity-head in the tube is possible. (The flow in the wide section below the capillary section is turbulent.)

Figure 2 shows the internal average head of the viscosimeter to be 13 cm, which should be added to the additional head indicated by the manometer. The slope of the straight line gives the flow characteristics of the instrument. η_0 is the known value of the viscosity of distilled water, which has been introduced chiefly to take care of the small inevitable differences in temperature.

A second set of experiments was conducted to determine the viscosity of suspensions for this clay while in the state of maximum dispersion obtained by adding sodium oxalate. Figure 2 shows that all the measurements for a certain concentration follow a straight line through the origin (head -13 cm). These suspensions therefore act like real liquids, with more or less increased viscosity. It would be misleading to plot this increase of viscosity over that of distilled water in terms of concentration, inasmuch as this increase appears to depend upon the character of the sediment as well as upon the degree of concentration.

It is necessary, however, to go further in attacking the underflow problem of some of the larger western reservoirs in which the sediment is in flocculated form. A set of experiments with the same 12 gram/100-cc suspension used above, but with varying degrees of flocculation, was conducted and is summarized in Figure 3. All experimental data used in plotting the points in Figure 3 were obtained without removing the sample from the viscosimeter. Only small amounts of dissolved salt were added in order to change the state of flocculation.

The data plotted in Figure 3 indicate that: (1) All points for the same state of flocculation appear to follow a straight line approximately at the same inclination as the line for dispersed sediment, but cross the line of zero-velocity at different points (plastic flow); (2) for the lowest velocities, the points seem to diverge from the straight line, decreasing the necessary force; (3) the pressure necessary to obtain a certain velocity increases with increasing degrees of flocculation.

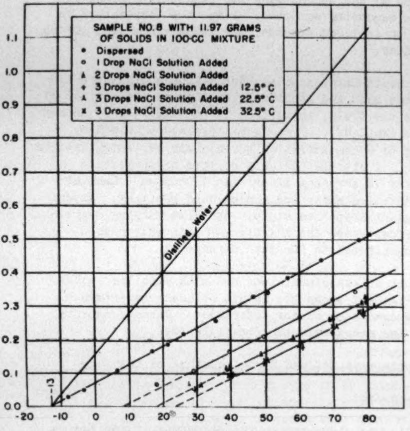


FIGURE 3 - EXPERIMENTS WITH DIFFERENT DEGREES OF FLOCCULATION IN THE SAME SAMPLE

The simplest interpretation of this diagram from the standpoint of the engineer is: The friction in the tube is composed of two parts, the "friction of the fluid" and the "solid friction" of the particles. The friction of the fluid is indicated by the curve for dispersed sediment, the additional solid friction being essentially independent of the velocity.

For other concentrations, similar sets of curves can be established, where the values of solid friction decrease with decreasing concentration. It may be mentioned that this solid friction depends upon the type and concentration of the sediment, as well as upon the type and concentration of dissolved matter. Therefore, the only reliable method of solving a practical problem is to obtain a sample of the flowing mixtures and determine the viscosity of this sample, taking every precaution not to change the state of flocculation. To accomplish this purpose, the following suggestions may be kept in mind: (1) Sampler, sample container, and viscosimeter should be absolutely free from any soluble matter, especially acid; (2) the sample should never come in contact with metal for any length of time; (3) the time between taking the sample and running the viscosity-test should be reduced to a minimum; (4) there should be no violent mixing of the sample during this time.

These suggestions should be strictly followed if satisfactory results are to be achieved. In the beginning of this chapter, the assumption was made that in laminar flow the shearing stress at any point in the cross-section is proportional to the total head-loss in the tube. This assumption does not apply for laminar flow of a plastic fluid, and this is the reason for the divergence of the lower portion of the curves from a straight line in Figure 3. Babbitt and Caldwell [1] developed an equation for the laminar flow of a plastic where the average velocity, v, is expressed in terms of tube diameter, D, shearing stress along the wall, τ_w, and its yield value, τ_s, a constant containing the acceleration of gravity, c, and the coefficient of rigidity, η

$$v = c(D/\eta)[\tau_w - (4/3)\tau_s + (1/3(\tau_s^4/\tau_w^3)] \qquad (2)$$

The coefficient of rigidity, η, is defined as the slope of the curve showing the relation between shearing stress and velocity, and is constant for a true plastic. In Figure 3, the plotted points appear to follow curves of this type. The straight line in Figure 3 approximate this equation without the latter term. Only at the lower end of the curve where (τ_s/τ_w) increases toward one is there a noticeable influence of the third term of equation (2), a condition which tends to shift the plotted points above the straight line. This fact is important as the intersection between the straight line, and the p-axes determine $(4/3)\tau_s$ instead of τ_s.

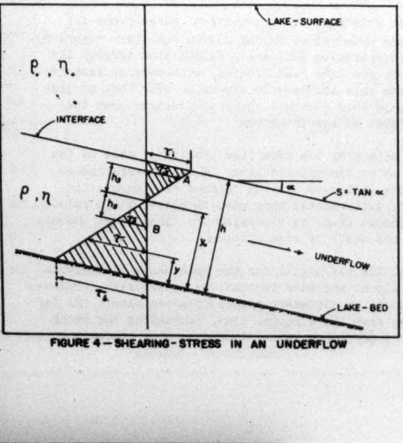


FIGURE 4 — SHEARING-STRESS IN AN UNDERFLOW

Application of the results on underflow--Unfortunately, not enough is known of the structure of turbulence to make an exact calculation of its influences; in fact, not even an estimate seems possible. Nevertheless, a qualitative description of the varying influences may help to throw some light upon the flow-condition in underflows, where an appreciable percentage of flocculated sediment is in suspension. In Figure 4, the force, $f = h(\rho - \rho_0)g \sin \alpha$, tends to accelerate a water-prism of the height, h, and of unit-base parallel to the bed. This force has to be counteracted by shearing stress, τ_1, at the interface and τ_b on the bottom. If we assume the composition of the underflow material to be uniform, the shearing stress changes linearly between these two extreme points. This distribution curve passes through zero at the distance y_0 from the bed. On either side of this point are located points A and B, where the shearing stress equals the stress corresponding to the solid friction in the particular suspension. In order to obtain a general idea of the position of these points, we may assume an underflow on a bed with the slope, s = 1:1,000, and a mixture corresponding to the lowest curve in Figure 3. This curve derived from experiments on a tube nine cm long and 0.04 cm in diameter crosses the $\Delta\rho$-axes at $\Delta\rho_s = 37$ cm of water. This pressure corresponds to the shearing stress, τ_s, along the wall of

$$(4/3)\,\tau_s = [37\pi \times 0.04^2 \times (1/4)]/(\pi \times 0.04 \times 9.0) = 0.041 \text{ gr}^*/\text{cm}^2 \tag{3}$$

where 1 gr* is the weight of a one-gram mass. Using this expression, we can write

$$\tau_s = 0.031 \text{ gr}^*/\text{cm}^2 = h_s(\rho - \rho_0)g \sin \alpha = h_s(0.075)(0.001) \tag{4}$$

and obtain $h_s = 410$ cm or 13.5 feet. A layer between zero and 27 feet in thickness, therefore, will move like a solid or a plug without any relative displacement of its parts, if all turbulence is prevented from reaching this region of the flow. In such a case this "frozen layer" divides the total flow into two distinctly separated parts. Above the frozen layer there may or may not be a remaining layer of flowing material between the plug and the lake-water. If this layer exists above the plug, a turbulent flow will result, and it is difficult to understand what factors could prevent mixing with the lake-water. Therefore, nonmixing underflows are very likely to have a τ_1 smaller than τ_s. In this case τ_1 depends only upon the velocity of the plug and the flow in the lake-water, and probably is governed by the National Bureau of Standards criterion θ

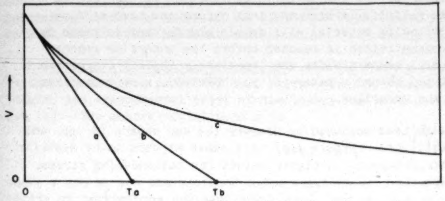


FIGURE 5—DECREASE OF VELOCITY RESULTING FROM DIFFERENT TYPES OF FRICTION

Unfortunately, the problem is complicated, even in this case, by the fact that the velocity of the plug itself and the value, τ_1, depend upon the flow and resistance in the lake-water which, however, are unknown quantities. Furthermore, the resistance of the lake-water is not constant with time, because the resistance is created only by the inertia of the lake-water, which itself is gradually accelerated.

The second part of the problem deals with the conditions below the plug. The whole layer below point B flows turbulent. The turbulence is probably created mainly along the bottom and spreads over the cross-section as in any normal turbulent flow. During the time of spreading, single units of turbulence are subject to an internal friction in the liquid, which is characterized by its viscosity. Figure 5 is an attempt to show, in general, how the destruction of kinetic energy for different types of friction takes place. The moving system may have the same velocity and the same friction force in the first moment for all three cases, that is, solid, viscous, or plastic friction. At the time, O, therefore, v, a representative velocity, and the rate of its decrease are the same for all curves. Curve a is obtained in the case of solid friction when the friction force and the rate of decrease are independent of the velocity, hence the curve is a straight line. Curve c is the usual line for normal viscous friction, in which the friction force and the decrease of velocity are proportional to the velocity itself. Hence, a curve that only reaches the time axis in the infinite as an asymtote is obtained and therefore it is meaningless to speak of the life-span of an eddy in viscous flow. Curve b, which represents the curve for plastic flow, is a combination of curves a and c. Here the friction force and the rate-of-velocity reduction decrease according to the curves in Figure 3, resulting in a slightly bent curve b, which still has a well-defined life span, T_b.

The existence of a finite life-span for eddies is essential for our problem. Eddies spread from the bottom with a certain maximum speed, and therefore are able only to reach a certain level during their life-span. In order that mixing does not occur, the eddies must already become too feeble to break through on reaching the interface. This second condition for the existence of a nonmixing underflow is formulated in a merely qualitative manner and needs more experimental work for practical application.

Results of past field-studies--Grover and Howard [5] have written a very comprehensive report on field-investigations made in the past. Several statements in this paper seem to prove that flocculation of the suspended solids is essential for the development of underflows. The authors state that the Colorado River evidently carries its suspended load in a state of partial coagulation. They also state "the soluble-salt content of the outflow (of Lake Mead) increases materially during the periods of turbid flow." Our own investigations indicate that perhaps it is more correct to say that an underflow will occur only when the soluble-salt content is high enough to grant a sufficiently high degree of flocculation.

A. D. Lewis in discussing the paper of Grover and Howard [5, pp. 757-759] cites similar examples as existing in southern African Lakes where occur "flows of flocculated silt along the bottoms of reservoirs under the comparatively clear water." Furthermore, he states that these underflows are possible only with minimum concentrations of 1.5 to 5 per cent and maximum concentrations of 25 per cent. These limits compare very well with the concentrations studied in Figures 2 and 3 of this paper. Lewis further states "flow becomes very sluggish and suddenly almost ceases near the upper limit of concentration." This possibly may be the "freezing" of a layer, when the shearing stress, τ_b, drops below the value, τ_s, of the suspensions. This shearing stress for concentrations above 25 per cent appears to be so high that the slope in these lakes is not sufficient to move a layer of the available thickness. He further states that underflows will develop only when the salinity is high and that during the time of flow under the still water of a lake, the underflowing material will settle and further increase concentration in the flow. If the maximum concentration is reached before the underflow reaches the lower end of the lake, the underflow will cease flowing and immediately deposit its sediment. J. C. Stevens in his discussion of Grover and Howard's paper [5, pp. 767-770], also emphasizes the close connection between floccuation and underflow.

The viscosity of clay-slurries has also been measured by Gregory [2] and others [3, pp. 466-495; 4, pp.532-557]. The viscosimeter as described in Figure 1 of this paper appears to be superior to other viscosimeters, such as the Stormer, inasmuch as higher values for the shearing stress, τ_w, can be obtained for undercritical flow.

Summary--(1) A comparatively simple method for measuring of the viscosity of clay suspensions is described. The method has the advantage that it can even be executed in the field.

(2) Measurements by this method show that a change in concentration influences primarily the viscosity, while the degree of flocculation determines the plasticity of a suspension.

(3) A general discussion of the results shows that the plasticity appears to be highly responsible for the existence of nonmixing underflows at high Reynolds numbers.

Future work--Future investigations of underflows, that are to be undertaken, should include both studies in the field and laboratory. The work in the field should include the recording of underflows as they occur, and the measurement of viscosity of the inflowing and outflowing mixture, as well as the underflow itself, whenever possible. Attempts should also be made to measure the velocity of underflows, as well as their depth and slope, and routine sampling of river water should be made. The laboratory work should be concentrated more in determining the life-span of eddies, as well as their shape and speed of propagation after their formation along the bed. Studies of this type would fit in rather closely with turbulence investigations in general. However, such studies must be made on suspensions, as the knowledge of the behavior of pure liquids as determined in wind tunnels will not yield the proper results, because of the different type of friction involved.

Acknowledgments--The author is grateful to the entire staff of the Enoree River Sediment-Load Laboratory for many valuable suggestions and especially to Richard G. Grassy and Dr. Gordon Rittenhouse for their assistance in conducting the laboratory work.

References

[1] Harold E. Babbitt and David H. Caldwell, Laminar flow of sludges in pipes with special reference to sewage sludge, Bull. Univ. Ill. Eng. Exp. Sta., ser. 319, v. 37, No. 12, 60 pp., 1939.

[2] W. B. Gregory, Pumping clay slurry through a four-inch pipe, Mech. Eng., v. 49, No. 6, pp. 609-618, 1927.

[3] Ralph E. Grim, Recent marine sediments: A symposium edited by Parker D. Trask, Amer. Assoc. Petr. Geol., 735 pp., 1939.

[4] Stina Gripenberg, Recent marine sediments: A symposium edited by Parker D. Trask, Amer. Assoc. Petr. Geol., 735 pp., 1939.

[5] Nathan C. Grover and Charles S. Howard, The passage of turbid water through Lake Mead, Trans. Amer. Soc. Civ. Eng., v. 103, pp. 720-732, 1938.

[6] National Bureau of Standards, Report on investigation of density currents, U. S. Dept. Commerce, Mimeo., 21 pp., March 10, 1936.

Soil Conservation Service,
U. S. Department of Agriculture, and Clemson College,
Greenville, South Carolina

ENGINEERING CALCULATIONS OF SUSPENDED SEDIMENT

E. W. Lane and A. A. Kalinske
(Presented by E. W. Lane)

The general theory of the vertical distribution of suspended sediment in a turbulent water stream has been sufficiently well established to permit its use in making calculations of the suspended material transportation in connection with engineering problems. It is the purpose of this paper to present simplified methods for making the necessary calculations of the total amount of sediment transported in suspension in a river or canal. Field-data is presented for purposes of checking the validity of the various approximations made, and to indicate the accuracy of the proposed calculations.

Vertical distribution of sediment--The turbulence-suspension theory of sediment-distribution vertically has been presented by O'Brien [see 1 of "Reference" at end of paper], Rouse [2], and others, and experimental proof of the theory has been indicated by Christiansen [3] and Richardson [4]. The general relationship is

$$\log_e (N/N_a) = -c\int_a^y \frac{dy}{\epsilon} \tag{1}$$

where N and N_a are the sediment concentrations at depths y and a above the bottom, c is the velocity of fall of the sediment considered, and ϵ is a so-called mixing coefficient. If the variation of ϵ with y is established then the integral can be evaluated. It is shown in the turbulence theory that at any point the unit shear, $\tau = \rho\epsilon(dV/dy)$, where V is the mean velocity at any depth y, and ρ is the water-density and is equal to (w/g), where w is weight per unit-volume. If the variation of τ and V with depth is known, then ϵ can be evaluated for various depths. For a wide stream, to which this analysis will be confined, it is known that $\tau = \tau_0[1 - (y/D)]$, where τ_0 is the bottom shear and equal to wDS, where D is the depth and S is the friction slope.

The vertical distribution of velocity varies with the stream cross-section; for wide streams it is closely approximated by the Prandtl-von Kármán logarithmic curve for velocity variation in turbulent flow. It can be written thus

$$V/V_m = 1 + (\sqrt{gDS}/kV_m)[1 + \log_e (y/D)] \tag{2}$$

where V_m is the mean velocity in the section, and k is von Kármán's universal constant equal to about 0.40. If Manning's formula is substituted for V_m, the quantity $(\sqrt{gDS}/kV_m)$ becomes $1.70\sqrt{g}\, n/D^{1/6}$, where n is the Manning roughness-factor.

Using equation (2) and the relationship for unit-shear for the case of wide streams an expression for ϵ is obtained

$$\epsilon = kD\sqrt{gDS}\,(1 - z)z \tag{3}$$

where z is the relative depth (y/D). This equation for ϵ indicates that this diffusion-coefficient is zero at the stream top and bottom and is a maximum at the mid-depth. Experiments on turbulence diffusion [5] indicate that ϵ does actually vary in this general manner even in narrow channels. If the expression for ϵ is now substituted in equation (1) the integration can be performed and the relative sediment-concentration (N/N_a) can be evaluated.

However, from a practical engineering standpoint the expression obtained is not very convenient to use. A much simpler expression would be obtained if it could be assumed that ϵ is constant throughout the stream-depth. Though this is not actually true, data on sediment-distribution in wide rivers, as will be shown later, indicate that such an approximation is valid for most practical purposes. Therefore, from equation (3) the average value of ϵ is calculated and assumed to be constant in any vertical section.

$$\epsilon_{ave} = D\sqrt{gDS}/15 \qquad (4)$$

Putting this constant value of ϵ into equation (1), the equation for sediment-distribution becomes

$$(N/N_a) = e^{-15t(z-a)} \qquad (5)$$

where $t = c/\sqrt{\tau_0/\rho}$ and for wide streams this is $c/\sqrt{gDS}$. This relation plots as a straight line on semi-logarithmic paper, and the concentration at any point in a vertical section can be determined by simply plotting the known concentration, N_a, and drawing a straight line through this point at a slope as determined from $-15t$. (Note that the factor 15 should be changed to 6.5 if the plotting is on a logarithmic scale to the base 10 instead of to the base e.) This is of considerable practical significance, since from a determination or measurement of sediment-concentration at a single point in a vertical section, if the sediment-composition is known, it is possible to determine the concentration at all other points in the vertical section by means of a simple calculation or graphical construction.

In Figure 1 is shown a plotting of field-data on suspended sediment-distribution in the Mississippi River and in Figure 2 is shown the velocity-distribution measurements. Note that a curve obtained using equation (2) with an assumed value of n equal to 0.03 fits the data quite well. The actual values of sediment-concentration at various depths are given in Table 1. The Mississippi River data were obtained and analyzed by the authors with the assistance of the United States Army Engineer Corps. The samples were taken at a point in the center of the River at Muscatine, Iowa, during the flood of September, 1938. The slope of the straight lines passing through the plotted points was taken at $-15t$ using the values of river-depth and slope shown. The value of velocity of fall, c, used for any range of sediment-size is the average value for the range considered. From the field-data shown and other data which is not presented due to

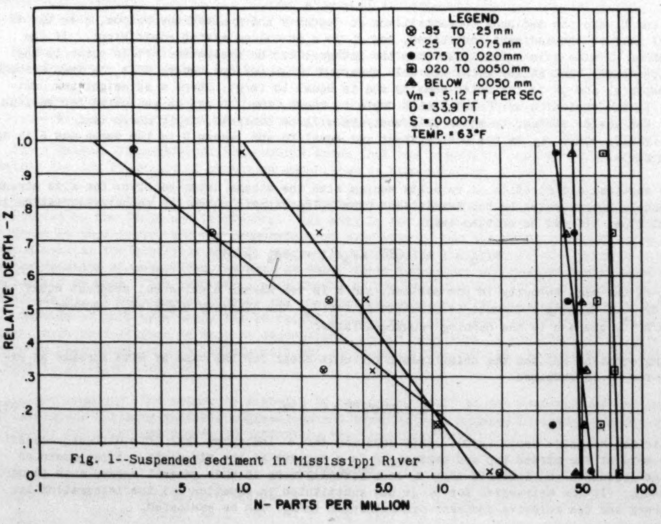


Fig. 1--Suspended sediment in Mississippi River

Table 1--Suspended-sediment-concentration measurements in Mississippi River at Muscatine, Iowa

(Total depth = 33.9 feet; S = 0.000071; mean velocity = 5.12 ft/sec; temperature = 63°F)

Distance above bottom, feet	Concentration in parts per million					
	Total	Size in mm				
		0.85 to 0.25	0.25 to 0.075	0.075 to 0.020	0.020 to 0.005	Below 0.005
0.6	217	19.5	17.1	55.6	77.1	47.2
5.4	173	9.5	9.9	36.0	64.0	53.6
10.9	184	2.6	4.6	50.0	73.3	53.7
17.9	163	2.8	4.2	42.6	62.0	51.4
24.9	168	0.84	2.5	47.0	73.7	43.9
32.9	151	0.30	1.1	38.2	65.1	46.1

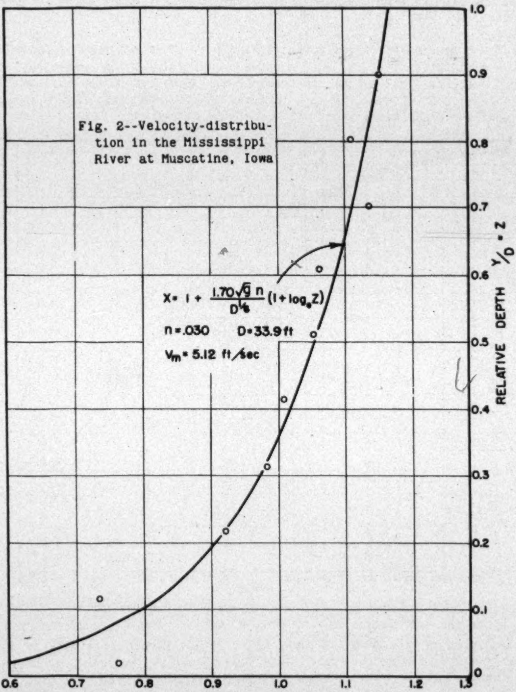


Fig. 2--Velocity-distribution in the Mississippi River at Muscatine, Iowa

lack of space, it appears that the approximate expression for sediment distribution as given in equation (5) is sufficiently accurate for most practical purposes. However, the fact should not be overlooked that the data and the analyses are for wide rivers, and also that the turbulence developed is due to the drag on an unconsolidated sand-bed. These analyses cannot be expected to apply where turbulence is developed due to roughnesses and flow-disturbing items such as rocks, shrubs, trees, or various artificial obstacles.

Total suspended load--If the distribution of sediment in any vertical section is known, then the total load, M, carried per unit-time, per unit stream-width, can be determined by multiplying the concentration per unit-volume at each point by the velocity at that point and integrating from top to bottom of the stream. In our analysis this amounts to combining equation (5) with the velocity-distribution, equation (2), and obtaining

$$M = V_m D N_a \int_0^1 x e^{-15t(z-a)} \, dz \qquad (6)$$

where $x = (V/V_m)$ and is given by equation (2). By taking e^{15ta} outside the integral we then have that $M = q \, N_a e^{15ta} \, P$, where q is the water-flow in cfs per unit-width and P is solely a function of the parameters t and $(\sqrt{gDS}/kV)$, which latter has been shown to be equal to $1.70\sqrt{g} \, n/D^{1/6}$. Thus the term P is a function of the parameter t and the relative roughness $(n/D^{1/6})$. Since the calculation of the term P is quite tedious its values have been determined and are shown in Figure 3. The range of values of t shown are those for which suspended-sediment transportation is of any significance and the values of relative roughness shown cover most hydraulics problems.

For the data for the Mississippi River shown in Figure 1, the total rate of sediment-transportation per unit-width of river, M, was computed by multiplying the concentration at each point by the measured velocity. The actual sum total of all size transported was found to be 1.85 pounds per second per unit-width. The work involved in obtaining this figure was quite laborious since it involved a graphical integration for each size-range. The value of M was then also determined from the expression: $M = V_m \, D \, N_0 \, P$, where N_0 was the concentration of any size-range at the zero-level as read from the plotting in Figure 1, and P was obtained from Figure 2. The value of M obtained in this manner was 1.89 pounds per second, thus indicating the general accuracy of the method of total suspended-load determination as outlined.

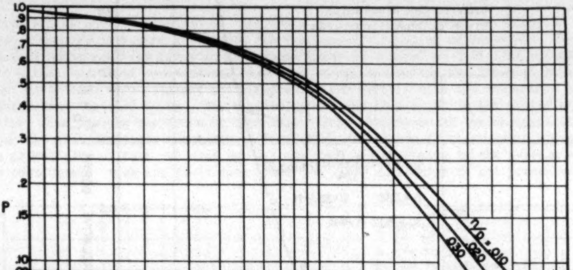


Fig. 3--Values of factor P for different values of parameter t

Another item of practical significance is the evaluation of the mean sediment-concentration in any vertical section. This mean value would, of course, by (M/q) and it is

$$N_{ave} = N_a \, e^{15ta} \, P \qquad (7)$$

When $a = 0$, then we have that $(N_{ave}/N_0) = P$, that is, the factor P is in reality the ratio of the average sediment-concentration in the vertical to the concentration at the zero-level. Obviously such a ratio approaches unity for very fine sediment.

Summary--Briefly, the analyses made indicate that so far as wide rivers are concerned the total suspended sediment transported can with fair approximation be found by measuring or determining the concentration at some one level, preferably somewhere in the lower half-depth, and finding the total rate of sediment carried per unit-time per unit-width from the expression $N_a e^{15ta} P$. The parameter t is equal to $c/\sqrt{gDS}$ in which c is the average fall velocity of the size range of sediment considered, g is the acceleration of gravity, D is the stream-depth, and S is the friction-slope. The factor P is obtained from a plotting indicating values of this term for various values of t and the relative roughness $(n/D^{1/6})$.

Theoretically then, field-measurements need only be made of the concentration of suspended material at a single level to permit the calculation of the total suspended load in the unit-width of stream in which the measurement was made. Obviously, measurements should be made at various sections across the stream since the mean velocity in the vertical section and the sediment-concentration varies transversely across any river. Also, as many measurements should be taken as can be economically analyzed and as the accuracy of the problem warrants.

It should be pointed out that the analysis given here can be used in conjunction with the determination of the suspended material under equilibrium-conditions from a consideration of the bottom composition and the depth and slope of the stream as discussed by the authors in a previous paper [6]. Theoretically this will permit the prediction of the total suspended-sediment transportation from a knowledge of the bed-composition and the hydraulic characteristics of a stream. The theory on which the method is based is fundamentally correct and the pertinent variables entering the problems are combined in such a manner so as to make the expressions dimensionally sound and very general. The approximations made have such a simplifying effect on the mathematical expressions that their use is warranted even though under certain conditions the accuracy may not be very great.

From a practical standpoint, however, the usefulness of the method is limited to the coarser sediments, since the fine material is uniformly distributed throughout the stream and a single accurate sample taken at any point in the stream should give the concentration with sufficient accuracy. The fine material cannot be accurately estimated from the bed-material composition because of the difficulty of determining with sufficient accuracy the amount of fine material on the bed, and also because equilibrium-conditions for the fine material are probably rarely reached. In most streams the fine material is the largest part of the sediment, but in many problems, such as those dealing with deposits in canals and rivers, the coarse material carried in suspension is usually the most important part.

This analysis of suspended-sediment distribution in a stream and the rate of its transportation is useful in comparing the relative accuracy of different sampling methods. Even though the expressions given for sediment-distribution have definite limitations, the values obtained approach the actual sediment-distribution sufficiently close to be used as a basis for comparing the errors obtained in total suspended-sediment transportation, as calculated from samples taken in accordance with various methods now in use. The principal points of the discussion of this paper by J. W. Johnson have been incorporated herein, and are gratefully acknowledged by the authors.

References

[1] M. P. O'Brien, Review of theory of turbulent flow and its relation to sediment-transportation, Trans. Amer. Geophys. Union, p. 487, 1933.
[2] Rouse, An analysis of sediment transportation in the light of fluid turbulence, U. S. Dept. Agric. Sedimentation Division, S.C.S.-TP-25, July 1939.
[3] J. E. Christiansen, Distribution of silt in open channels, Trans. Amer. Geophys. Union, Part II, p. 478, 1935.
[4] Richardson, Suspension of solids in a turbulent stream, Proc. R. Soc London, v. 162, p. 583, 1937.
[5] A. A. Kalinske, Relation of statistical theory of turbulence to hydraulics, Trans. Amer. Soc. Civ. Eng., v. 105, p. 1547, 1940.
[6] E. W. Lane and A. A. Kalinske, Relation of suspended to bed-materials in rivers, Trans. Amer. Geophys. Union, p. 637, 1939.

University of Iowa,
Iowa City, Iowa

SOME EXPERIMENTS ON THE TRANSPORTATION OF SUSPENDED LOAD

Vito A. Vanoni

Introduction

The purpose of this paper is to present briefly the results of experiments on the transportation of a suspended load of sediment by water. In the experiments, measurements were made of the total load carried by such flows and of the distribution of the load in the flow. This work was done by the Cooperative Laboratory of the Soil Conservation Service and the California Institute of Technology, as a part of the research program of the laboratory having to do with the mechanics of entrainment, transportation, and deposition of sediments. The objective of these studies is to clarify the mechanism of erosion and to establish physical laws governing erosion-phenomena that will be of assistance in the work of the Soil Conservation Service. The present paper is submitted as a contribution to this objective.

Analytical background

The theory of transportation of suspended load is based on the fundamental equation for turbulent transfer [see 1 of "References" at end of paper]

$$N = -\beta|v'|\ell\ (dn/dy) = -\epsilon_n\ (dn/dy) \qquad (1)$$

where N is the transfer of the property n in the y-direction per unit-time and unit-area, β is a numerical coefficient which gives a measure of the correlation between the turbulent fluctuations, $|v'|$ is the average of the velocity-fluctuations in the y-direction, and ℓ is the mixing length. The quantity, ϵ_n, which is equal to $\beta|v'|\ell$, is known as the mixing or transfer-coefficient for the property, n. When n is the momentum, the familiar equation for shear results

$$\tau = \beta|v'|\ell\ [d(\rho U)/dy] = \rho\ \beta|v'|\ell\ (dU/dy) = \rho\ \epsilon_m\ (dV/dy) \qquad (2)$$

where U is now the velocity normal to y, ρ is the mass-density of the fluid, and ϵ_m is the transfer-coefficient for momentum. For the case of suspended sediment the rate, N_s, at which material is transferred is given by

$$N_s = -\beta|v'|\ell\ (dC/dy) = -\epsilon_s\ (dC/dy) \qquad (3)$$

where n now becomes C, the sediment-content per unit-volume, and ϵ_s is the sediment-transfer coefficient. The quantities β, $|v'|$, and ℓ and hence the mixing coefficients, ϵ_m and ϵ_s, in equations (2) and (3) are not necessarily the same [1].

For steady uniform conditions the rate of upward transport of material by turbulence [equation (3)] is balanced by the rate of settling, Cw, due to the gravitational force, or

$$-\epsilon_s\ (dC/dy) = Cw \qquad Cw + \epsilon_s\ (dC/dy) = 0 \qquad (4)$$

where C is now the amount per unit-volume of the fraction of the sediment having a settling velocity, w, in the still fluid, the flow is in the horizontal direction and the y-axis is vertical. Solution of equation (4) gives

$$\log_e\ (C/C_a) = -w\int_a^y (dy/\epsilon_s) \qquad (5)$$

where C_a is the concentration at an arbitrary level y = a. In order to integrate the right-hand side of equation (5) the mixing coefficient, ϵ_s, must be expressed as a function of y. Because such a functional relationship is not available the assumption usually is made that ϵ_s is equal to ϵ_m and the relationship for the latter quantity as given by equation (2) is introduced into equation (5), giving

$$\log_e\ (C/C_a) = -\rho w\int_a^y (1/\tau)\ (dU/dy)\ dy \qquad (6)$$

Introducing the condition that the shear, τ, is distributed linearly gives

$$\log_e\ (C/C_a) = -\rho\ (w/\tau_0)\int_a^y [d/(d-y)]\ (dU/dy)\ dy \qquad (7)$$

where τ_0 is the shear at the channel bottom for a two-dimensional flow of depth d. By assuming that the velocity-distribution follows the universal logarithmic velocity-defect law

$$(U - U_{max})/\sqrt{\tau_0/\rho} = (2.3/k)\log_{10}(y/d) \tag{8}$$

and an expression for the velocity-gradient, (dU/dy), can be obtained by differentiation and substituted into equation (7). Performing this substitution and integrating gives the expression

$$(C/C_a) = \left\{[(d - y)/y]\,[a/(d - a)]\right\}^z = H^z \tag{9}$$

which was first presented by Rouse [2], and in which $z = (w/k)\sqrt{\tau_0/\rho}$. Here k is the universal constant for turbulent exchange, having an average value of 0.4 for clear fluids. For two-dimensional open channels the quantity, $\sqrt{\tau_0/\rho}$, is equal to $\sqrt{gdS}$, where S is the slope of the channel. Equation (9) is plotted on Figure 1 for several values of z and for a held constant at 0.05 d. It will be noted that the result does not give an absolute value for the concentration and that, therefore, it does not permit the calculation of the total load of the flow. To make this possible the value of C_a is required. The development and clarification of the theory of suspended load is due mainly to Schmidt [3], Leighly [4], O'Brien [5], and von Kármán [1]. The development presented here is due to von Kármán.

Experimental procedure

The experiments reported below were performed in a flume 33-1/4 inches wide by 12 inches deep by 60 feet long, a diagram of which is shown in Figure 2. This flume was first constructed as described by Oaks and Knapp [6] and subsequently revised to conform to the Figure. By making a closed-circuit system it was possible to circulate the sediment directly with the water. Since the lowest velocity is always in the flume-section, material that can be carried through this section will not deposit in the return pipe or in any other part of the system.

The rate of flow was measured by a venturi-meter and controlled by the speed of the pump which was driven by a two-speed electric motor through a variable ratio vee-belt transmission. All of the head developed by the pump goes to overcome resistance to flow and is finally converted into turbulence, so it was desirable to keep the head and the resulting turbulence as low as possible. With the above circuit a head of only three feet circulated a flow of about five cubic feet per second. The adjustable diffuser lid at the inlet made it possible to bring the water into the flume at the desired equilibrium-depth and uniform-flow conditions were attained in a very short reach of the flume. Figure 3 shows the inlet end of the flume with the diffuser-lid and the downstream end of the transition-section from the pipe to the open channel. The slope of the flume was adjustable by means of four jack-screw supports. The sides of the channel were smooth, while the bottom was roughened with 0.88-mm sand cemented to the steel with bitumastic paint.

Velocities were measured with a 3/16-inch diameter pitot-static tube of the Prandtl [7] standard design. The distribution of sediment in the flow was determined from samples siphoned from the flume through a 5/16-inch brass pipette, shaped much like a pitot-tube. The inlet of the sampler tube was directed upstream and the rate of siphoning was adjusted so that the entrance-velocity coincided with the stream-velocity at the sampling point. The velocity in the sampler was determined from the time required to fill a liter bottle and from the area of the sampler tip, while the stream-velocity, at the point, was determined in advance with the pitot-tube. Figure 4 shows the sampling set-up in operation with the discharge end of the flume in the background. The elevator carrying the bottle and the end of the siphon allows adjustment of the head, and hence of the velocity in the sampler tube. In general, three one-liter samples were taken at each point, the sediment filtered out and dried and weighed. At the right of Figure 4 may be seen the instruments and the carriage used in making readings in the flume. Note also the window in the side and one of the adjustable screw-jack supports. The numbers on the wall of the flume represent distances in feet from the inlet and are referred to as station.

The average load of the flow was determined from samples siphoned from the collecting tank (see Fig. 2) through a 3/4-inch pipe, so constructed that the inlet end was directed vertically upward against the flow during sampling. In order to get a representative sample, the pipe was moved systematically so fluid was drawn from the entire cross-section of the flow. These samples gave an average concentration, C_m, in weight per unit-volume, which, when multiplied by the rate of discharge, q, in volume per unit-time, gives the total sediment-transport, G, in weight per unit-time.

Figure 5 shows the size-distribution curves for the three silica sands used as suspended loads. These curves are plotted on logarithmic-probability coordinates, according to a method developed by Otto [8]. The table in the Figure gives geometric-mean sieve-size, d_m, the geometric standard deviation, σ_g, and the mean sedimentation diameter, $\overline{d_s}$, for each sand. The mean sedimentation-diameter is defined as the diameter of the sphere of the same material which has a settling velocity, w, equal to the velocities of the center of mass of a group of particles

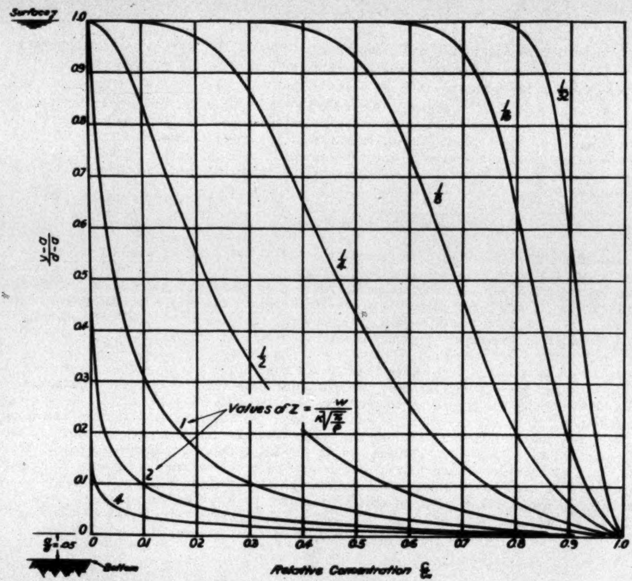


Fig. 1--Distribution of suspended load according to equation (9)

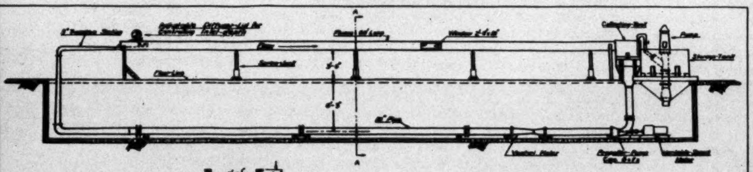

Flow
Pump
Storage-Tank
Collecting-Tank
Venturi Meter
A
A
3'-6"
6'-5"
8" Pipe
1'-0"
3'-6"
6'-6"
Section Through A-A

Fig. 2--Closed-circuit flume for suspended-load studies

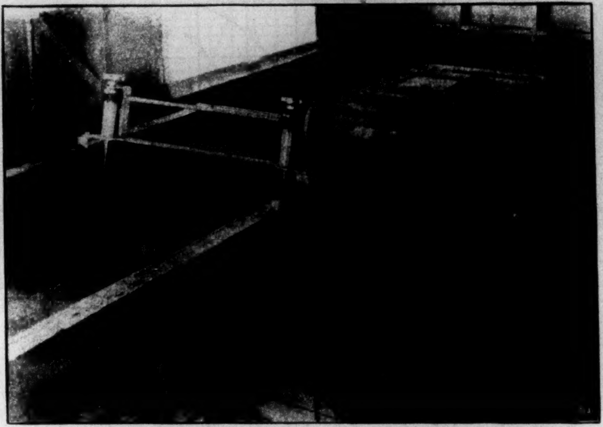


Fig. 3--Inlet to flume showing diffuser-lid controlling inlet-depth and downstream end of transition from pipe to flume

representative of the sand. This diameter was determined through direct settling velocity measurements.

Results

Velocity-distribution--Figure 6 shows velocity-distribution curves for various stations along the flume with and without sediment. It will be noted that near the center, the velocity-profiles are all nearly identical, indicating that the effect of the side wall is small and that

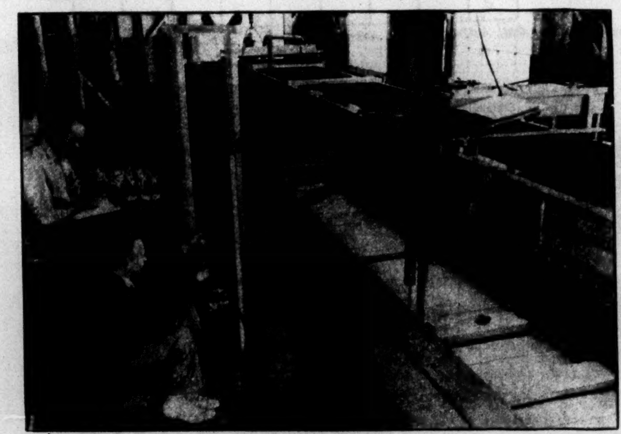


Fig. 4--Set-up for taking suspended-load samples

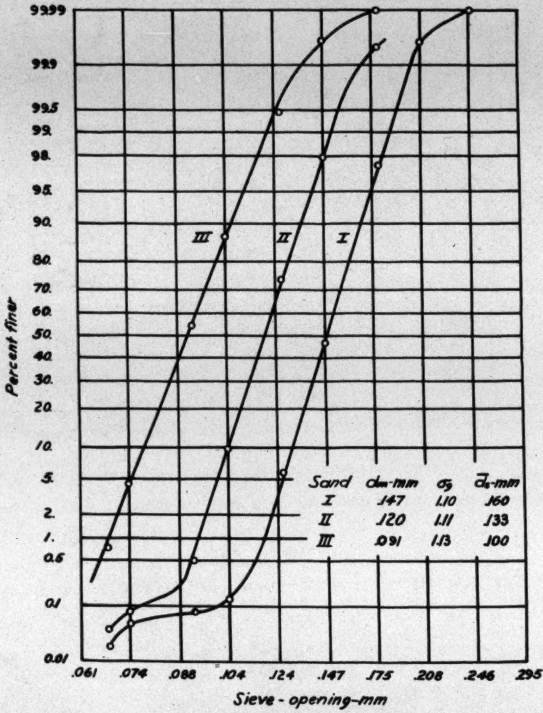


Fig. 5--Logarithmic-probability plots of size-distribution of sands used as suspended load

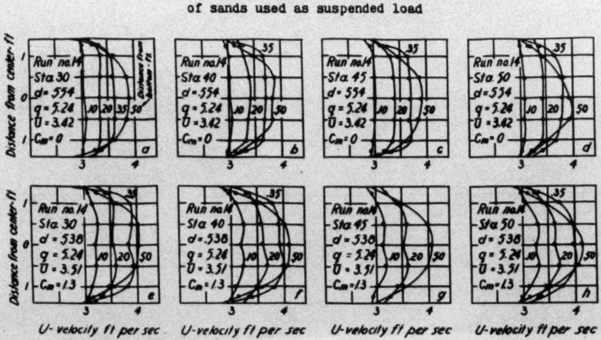


Fig. 6--Typical velocity-distribution curves over cross-section of flume

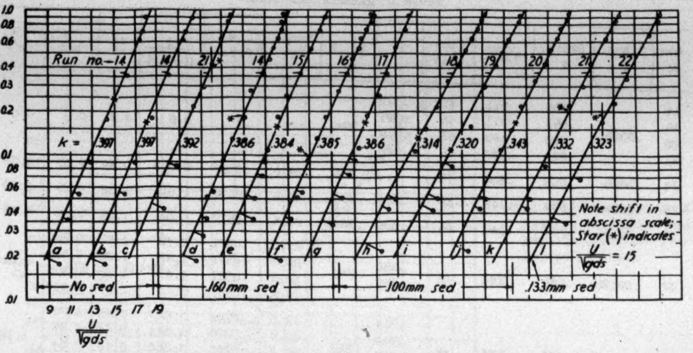


Fig. 7--Semi-logarithmic plot of velocity-profiles on center of flume

a two-dimensional condition is closely approximated. The curves also show that uniform flow is established in the flume, since the velocity is not appreciably different at the various stations.

In Figure 7 are shown semi-logarithmic plots of velocity-profiles on the center line of the flume for no sediment-load, and for loads consisting of each of the three sediments used in the experiments. The solid lines show the logarithmic distribution as given by equation (8) while the circles show the experimental data. The data follow the logarithmic law very closely except near the bottom where the measured velocities exceed those predicted from the law. Since this departure is small and occurs over a small portion of the flow, the assumption of logarithmic velocity-distribution introduces little error. The slopes of the curves on Figure 7 are inversely proportioned to k, the universal constant in the logarithmic velocity-law [equation (8)], and should be the same for all curves if k is actually constant. The slopes are not constant as may be seen from the Figure and, therefore, k varies. Values of k for the above measurements are shown in Figure 7 and in Table 1, and indicate that the presence of sediment tends to decrease k.

Sediment-distribution--Figure 8 is a logarithmic plot for the center line of the flume of

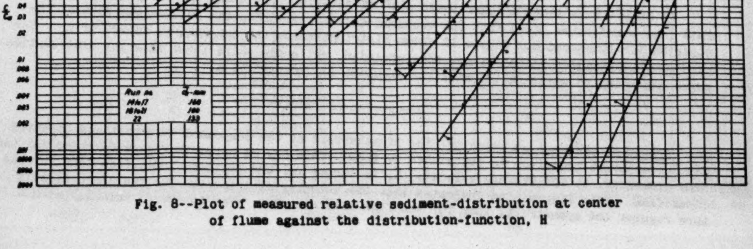


Fig. 8--Plot of measured relative sediment-distribution at center of flume against the distribution-function, H

Table 1--Summary of results

Run No.	Slope, S	Depth, d	$\sqrt{gdS}$	Station	k	Av. k	Temp., °C	w f.p.s.	$z = \frac{w}{k\sqrt{gdS}}$	z_1	C_a g/l	C_m g/l
14	.0025	.554	.211	40	.397	.394	----	.0	0.0	0.0	0.0	0.0
14		.554	.211	45	.397							
20		.462	.193	45	.389							
21		.234	.137	45	.392							
14	.0025	.538	.208	45	...	.386	24.0	.0590	0.735	0.89	9.09	1.33
15	.0025	.274	.148	45	.384	.384	21.0	.0577	1.02	1.02	5.25	0.59
16	.00125	.537	.147	45	.385	.385	21.5	.0577	1.02	1.05	3.02	0.59
17	.00125	.269	.104	45		.386	20.0	.0571	1.42	1.62	0.535	0.048
					.386		20.0	.0571	1.42	1.08	0.036	
					.386		19.3	.0567	1.41	1.45	0.995	
							19.6	.0567	1.41	1.47	0.416	
18	.00125	.462	.136	45	.314	.317	19.0	.0269	0.629	0.53	4.79	1.18
					.314		20.0	.0275	0.644	0.54	4.89	
					.317		22.0	.0285	0.660	0.48	3.54	
					.324		21.6	.0285	0.646	0.54	4.25	
19	.00125	.236	.0975	45	.334	.330	23.2	.0292	0.897	0.63	0.949	0.17
				40	.334		21.1	.0282	0.866	0.64	0.999	
				40	.334		19.2	.0272	0.835	0.69	1.20	
				45	.320		20.3	.0275	0.881	0.68	1.44	
				45	.320		20.5	.0278	0.891	0.68	1.29	
20	.0025	.461	.193	45	...	.349	22.0	.0285	0.423	0.34	4.27	
21	.0025	.234	.136	45	.332	.332	19.7	.0275	0.609	0.42	3.42	
22	.0025	.295	.164	45	...	.341	17.8	.0407	0.775	0.66	6.75	

the measured relative concentration, (C/C_a), against the distribution-function, H, as given by equation (9). For these calculations $a = 0.05\ d$. The fact that the curves on the logarithmic plot are straight lines indicates at once that the distribution follows the form of equation (9). The slopes of the curves on this plot give the value of the exponent, z, in the equation.

If the theory is correct, then the value, z, obtained from the slope of the lines on Figure 8, should agree with that given in equation (9), that is, $z = w/k\sqrt{gdS}$. In Table 1 the values of z and z_1 have been tabulated. Table 1 also shows C_a, the value of the concentration at the level, $y = a$, for each of the sediment-profiles, as well as C_m, the average concentration for the entire flow. These concentrations have been reported in grams per liter, which is equal, very nearly, to tenths of one per cent by weight. This Table also reports the temperature at which the measurements were made and the corresponding average settling velocity of the sediment comprising the suspended load. It may be seen immediately that the values of z and z_1 are not always equal, and that hence some of the assumptions made in developing the theory are not valid. In general, z_1 is less than z, indicating that the actual distribution was more uniform than that predicted by the theory. This point will be discussed at greater length below.

In Figure 9 is shown a logarithmic plot of equation (9) in the form, $\log (C/C_a) = z_1 \log H$. This figure indicates again that the measured sediment-distribution follows the form of the distribution-function, H. Figure 10 shows distribution-curves for various values of z_1. The circles show measured values of the concentration, while the solid lines show the distribution-curve according to equation (9) with the exponent z_1, instead of z.

Discussion of results

Effect of sediment on velocity--The first effect of the suspended load that was observed was the apparent reduction in resistance to flow. This may be noted in Figure 6, where for the same discharge, q, the average velocity, $\bar{U}$, is larger for the sediment-laden flow than for the clear flow. This Figure also indicates that the velocity-distribution for the clear flow is more regular and symmetrical than for the flow with sediment. The increased velocity with a

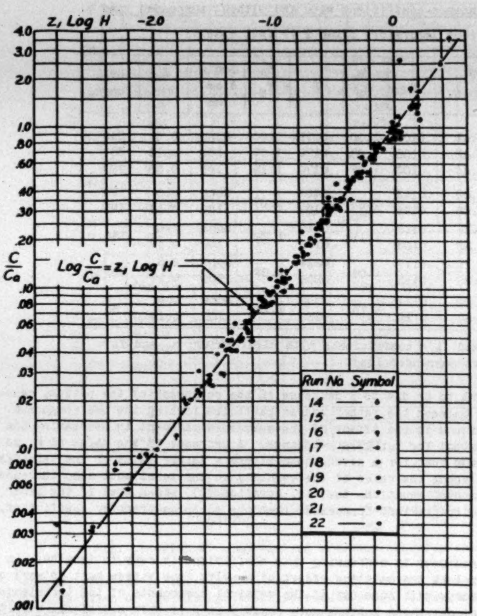


Fig. 9--Plot of measured against calculated sediment-distribution at center of flume

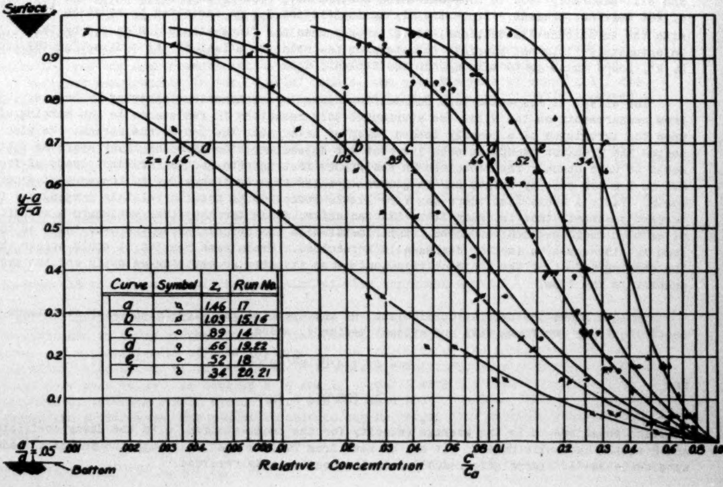


Fig. 10--Plot of measured and calculated sediment-distribution at center of flume

Table 2--Resistance-coefficient with and without suspended load

(For laboratory flume 2.77 feet wide)

Run No.	d, feet	$\bar{V}$, f.p.s.	n	$\frac{n_w}{n_s}$	f	$\frac{f_w}{f_s}$	Sed.-diam., mm	$\bar{C}$, %	Rel. rough.
	.496	3.49	.0108	1.00	.0192	1.00	None	0.0	340
8-10	.484	3.62	.0105	1.03	.0179	1.07	.160	0.16	330
17-20	.475	3.64	.0103	1.05	.0172	1.12	.160	0.33	320
14	.554	3.56	.0113	1.05	.0201	1.07	None	0.0	190
14	.538	3.65	.0108		.0187		.160	0.13	185
18	.462	2.28	.0114	1.11	.0215	1.22	None	0.0	160
18	.462	2.52	.0103		.0176		.100	0.12	
20	.461	3.16	.0117	1.04	.0224	1.09	None	0.0	160
20	.462	3.30	.0112		.0205		.100	0.11	
21	.234	2.05	.0124	1.10	.0306	1.22	None	0.0	80
21	.234	2.27	.0113		.0250		.100	0.11	

Note: n_w and f_w = coefficients with clear water; n_s and f_s = coefficients with suspended load.

sediment-load was first thought to be due to a decrease in the roughness of the bottom, caused by a deposit of fine sediment between the rather coarse particles forming the bed-roughness. A more tenable explanation was found in the effect of the suspended sediment in decreasing the value of k, the universal constant for turbulent exchange. A decrease in the value of k, as may be seen from equation (8), means that for a given shear stress a larger value of the velocity-gradient must occur, and that hence the value of the velocity at any level must also increase. Inspection of the momentum-transfer equation, that is, equation (2), shows that if the shear is kept constant, while the velocity-gradient increases, then the momentum-transfer coefficient, ϵ_m, must decrease.

The effect of suspended sediment in decreasing this coefficient is easy to imagine. In order to support the sediment against the settling effect of gravity, the stream must do work on the sediment. This work or energy must come out of the vertical components of the turbulence, and will naturally tend to damp out these motions more rapidly than if this additional damping effect were not present. Since the mixing coefficient, ϵ_m, as indicated by equation (2) varies with the turbulence-fluctuations, it is reduced when the fluctuations are damped by the sediment. Unfortunately it is not possible to determine the relative effect of the sediment on the factors β, V', and ℓ which go to make up the coefficient, ϵ_m.

The effect of suspended load in reducing channel-resistance was observed by Buckley [9] from measurements on the Nile. He attributed this reduction in resistance to the damping effect upon the turbulence of a heavily loaded layer of water near the bed of the stream. He also expected the greatest reduction when a stream was depositing, for then the layer near the bottom would be most dense. The reduction in resistance that he obtained for sediment loads of from 0.1 to 0.2 per cent by weight was in general greater than that obtained in the present experiments. Table 1 shows that there was very little reduction in k or very little damping for the largest sediment, that is, runs 14 to 17, inclusive, while for the finer sediments a reduction of as much as 20 per cent occurred. Experiments with the coarse sediment showed that, as the load was increased, a further decrease in k resulted. From these results it would appear that the damping effect of the sediment is dependent on its size or settling velocity and the amount present in the flow.

Table 2 shows the Manning coefficient, n, and the familiar pipe-friction or resistance-coefficient, f, for flows with and without sediment, where

$$n = (1.486/\bar{U})\, R^{2/3} S^{1/2} \tag{10}$$

and

$$f = 8g\, (RS/\bar{U}^2) = 8g/c^2 \tag{11}$$

In these equations, U is the average velocity for the cross-section, c is the Chezy coefficient, and R is the hydraulic radius. It may be seen from Table 2 that, although the sediment-loads were quite small, appreciable reduction in the coefficients resulted.

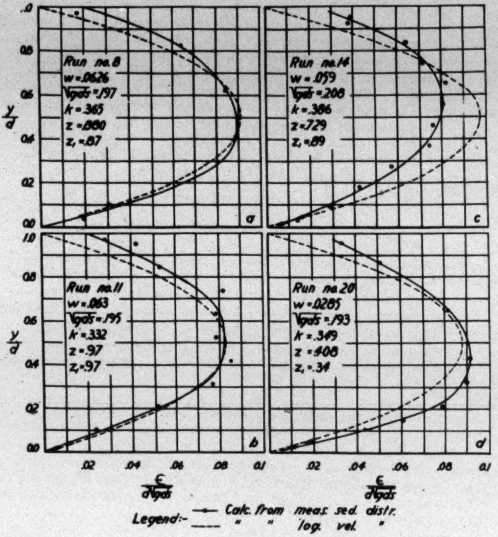


Fig. 11--Plot of momentum and sediment-transfer coefficient

As remarked previously, the measured sediment-distribution at a vertical cross-section had the same form as given by the theory, that is, equation (9). However, the exponent, z, given by the theory, did not agree with the exponent, z_1, obtained from the plots of the experimental data (Fig. 8). For the coarsest sediment, the two values of z agreed quite closely, but for the finer material, z_1 was always less than z, indicating that the sediment was more uniformly distributed than predicted by the theory. The fact that the form of the theoretical sediment-distribution follows the measurements agrees with the findings of Christiansen [10] on the studies of sediment-measurements in the Imperial Canals, and with the work of Rouse [11], who verified the fundamental equation for turbulent sediment-transfer with artificially produced turbulence.

It may be seen that the absolute values of the relative sediment-concentration obtained from the theoretical calculations do not agree with the experimental measurements. This lack of agreement may be considered the result of assuming that the coefficient, ϵ_s, for sediment-transfer is equal to the coefficient, ϵ_m, for momentum-transfer. In momentum-transfer a correlation is required between the vertical and horizontal components of velocity-fluctuation. However, in the case of sediment-transfer such a correlation is not necessary and a purely random turbulence can transport sediment. This would tend to make ϵ_s larger than ϵ_m, which in turn would result in z_1 being smaller than z. Such a trend is observed in the case of the two finer sediments (runs 18 to 22), and confirms the point of view expressed above.

For all of the runs with the coarsest material, z and z_1 are about equal. This latter result cannot be explained in terms of the action of the random turbulence, and it must be due to some other cause. An explanation is offered in terms of the intensity of the turbulence-fluctuations and the settling velocity, w, of the sediment. The intensity of turbulence at a particular level varies about some mean value. As long as w is small, compared with the mean turbulence-intensity, most components of turbulence will exceed w and can lift sediment. However, as the sediment becomes coarser and w increases, the weaker turbulence can no longer lift sediment and a reduction in ϵ_s occurs.

The difference between ϵ_s and ϵ_m, observed in the experiments, is explained above in terms of (1) random turbulence, which tends to increase ϵ_s, and (2) the relative magnitudes of the turbulence-intensity and the settling velocity of the sediment, which has the opposite tendency. If these two opposite effects act simultaneously, then, for some size of material, they cancel, and ϵ_s and ϵ_m are equal. For material coarser than this size, the second effect may be expected to exceed the first, resulting in ϵ_m larger than ϵ_s, and a less uniform sediment-distribution than expected from the theory. The size of the sediment in runs 14 to 17 was apparently correct for balancing the two effects outlined above, since the two coefficients are equal and the theoretical and measured sediment-distributions are in agreement.

Figure 11 shows dimensionless plots of characteristic values of ϵ_s and ϵ_m. ϵ_s has been calculated from equation (4) and measured sediment-concentrations, while ϵ_m is calculated from the expression.

$$(\epsilon_m/d\sqrt{gdS}) = k\,[(d - y)/d]\,(y/d) \qquad (12)$$

which is obtained from equations (2) and (8) and the assumption of linear distribution of shear. The circles represent values of ϵ_s, obtained from the experiments, and the solid line is a curve fitted to these values. ϵ_m is shown by a dotted line. It is seen that, in the case of the coarse sediment, the two coefficients agree very closely, while for the finer material, ϵ_s tends to be larger than ϵ_m. In estimating the effect of the difference in the two coefficients on the sediment-distribution, it must be noted [equation (5)] that the coefficient appears in the distribution-equation under an integral sign and that, therefore, the difference exerts a cumulative effect.

The curve for ϵ_s indicates that this coefficient has a finite value at the surface of the flow, while the coefficient ϵ_m goes to zero at the surface. The latter coefficient vanishes at this point because the correlation between the velocity-fluctuations goes to zero since the shear also goes to zero and no reason for a correlation exists. However, these uncorrelated fluctuations can still transport sediment and material is to be found right at the surface. This general tendency for the measured concentrations near the surface to exceed those indicated by the theory [equation (9)] is shown in Figures 8, 9, and 10.

Close inspection of Figure 6 will show that velocity-curves e to h, which are for a sediment-laden flow, tend to be less symmetrical and less uniform than curves a to d, which are for clear water. This effect was noted in all experiments and in some cases was very pronounced, and appeared to induce secondary circulations into the flow. These effects were so pronounced, even though the total load of the stream was small, that one is tempted to attribute some of the secondary currents that have been observed in natural streams to the sediment-loads.

These currents have been used to explain the fact that the maximum velocity occurs below the surface, but the cause of the secondary motion is not completely understood. It is felt that these currents, and hence the velocity-distribution, may be accounted for, at least in part, by the action of the sediment. If the concentration at a level varies even slightly in the transverse direction, a secondary circulation can be induced. The fluid with the higher sediment-load is heavier than the surrounding fluid and sinks towards the bottom, setting up a density-current that is vertically downward at the section of high concentration.

Observations of the sediment in motion showed that the material was carried in a series of clouds that appeared to be rolled up from the bottom in streaks or bands. The rolling motion in this process appeared to be the same as the motion of a wheel rolling downstream. The streaks traveled across the flow somewhat but, in general, they made a stable pattern and there were usually five or more longitudinal bands in the 33-inch-wide flume in the present experiments. The distance between these bands was approximately equal to the depth of the water.

From a practical point of view, information on the capacity of a stream to carry suspended load is of utmost importance. In the present experiments, there is some question as to whether or not sufficient material was added to the flow to load it to saturation. Some of the smaller flows may have been loaded; however, it is quite certain that the higher flows were not. Study of these data indicates that the average concentration, C_m, can be expressed as a power function of the boundary-shear, τ_0. The exponent in this expression appears to increase as the sediment becomes finer.

The findings of this study have shown that addition of sediment to a flow causes the velocity to increase. It is of interest at this point to examine the effect of this tendency upon the sediment-transporting capacity of a flow. One is tempted to conclude at once that increased velocity will naturally result in more load; however, it must be noted that the bed-shear, τ_0, is actually reduced because when the velocity is increased the depth is decreased. This means that the particles in the bed are actually subjected to less drag and that the ultimate sediment-transporting capacity is probably reduced. This view is compatible with the statement that the sediment damps the turbulence and permits the establishment of an upper limit of load or capacity. If the increased velocity due to a sediment-load also increases the capacity, it is obvious that the process would be unstable and that the capacity-load would be difficult to define.

The problem of the transportation of suspended sediment is intimately associated with turbulence and, therefore, it is recognized as a difficult one. It is now clear that added complications are introduced into the sediment-problem, since, not only is turbulence involved, but the sediment changes the turbulence itself, the amount of the change apparently depending upon the amount and size of the material in suspension. Where, in a clear stream, the velocity can be expressed in terms of certain constants which characterize the turbulence-mechanism, in sediment-laden flows, these factors are now functions of the sediment-load and sediment-characteristics. For this reason, the use of the turbulence-characteristics of clear flows in the development of sediment-transportation theories must be adopted with caution.

Conclusions

(1) The theory for the distribution of suspended load, which assumes that the exchange-coefficients for momentum and sediment are equal, does not agree with the experimental measurements.

(2) The form of the theoretical distribution law [equation (9)] agrees very closely with the measurements, indicating that the mechanisms of momentum and sediment-transfer are similar.

(3) The difference between the theory and measurements may be expressed in terms of the theoretical exponent, z, and the measured exponent, z_1, in equation (9). In the present experiments, the value of z_1 was less than z for the fine sediment, while for the coarsest material used the two exponents agreed closely. If still coarser material were used, it appears probable that z_1 would be larger than z. Since, the smaller the value of the exponent the more uniformly the sediment is distributed, the above result means that the flow was capable of more easily suspending the fine sediment than the theory indicated.

(4) For fine materials, the coefficient for sediment-transfer, ϵ_s, is larger than ϵ_m, the coefficient for momentum-transfer, while, as the sediment becomes coarser, the two coefficients become more nearly equal, and finally when the size of the material is increased further, ϵ_m is expected to exceed ϵ_s.

(5) The physical explanation of the above results may be presented in terms of two effects: (1) Purely random turbulence is effective in sediment-transfer, while for momentum-transfer a correlation between the velocity-fluctuations is necessary; (2) as the sediment-size, and hence the settling velocity, increases, the weaker components of the turbulence exert less and less influence insupporting sediment.

(6) The addition of sediment to a clear flow causes the velocity to increase, the increase apparently depending on the size and amount of sediment in the flow. This effect reduces the apparent resistance or roughness-coefficient of a channel.

(7) The addition of sediment to a flow results in a decrease of ϵ_m, the transfer-coefficient for momentum, and in an increase in the velocity-gradient and velocity.

(8) Sediment in a flow tends to reduce k, the universal constant for momentum-transfer.

(9) Conclusions 6, 7, and 8 can be related to the effect of sediment in damping the turbulence. The sediment, which must be supported by the turbulence, produces an added resistance-force on the eddies that is not present in clear flows, and hastens their dissipation. This added resistance-force also reduces the effectiveness of the eddies in transferring momentum.

(10) Suspended load appears to induce secondary circulations not noticed in clear flows. This effect may be responsible, at least in part, for the circulation in natural streams that causes the depression of the maximum velocity below the surface.

(11) The increase in velocity, due to an addition of sediment to a clear stream, probably does not give rise to an increased sediment-transporting capacity, since it is accompanied by a

decrease in the shear or drag at the boundaries. This statement is compatible with the ideas that sediment damps the turbulence and that a stream has a fixed capacity to transport material.

Acknowledgments--The writer wishes to acknowledge the friendly assistance of Professors Theodor von Kármán and Robert T. Knapp and of the staff of the Cooperative Laboratory.

The work was carried out with the aid of Work Projects Administration, Official Project No. 65-2-07-58, Work Project No. PS-11496.

References

[1] Th. von Kármán, Some aspects of the turbulence problem, Proc. Fourth Internat. Cong. Applied Mech., Cambridge, England, 1934.
[2] Hunter Rouse, Modern conceptions of the mechanics of fluid turbulence, Trans. Amer. Soc. Civ. Eng., v. 102, p. 463, 1937.
[3] Wilhelm Schmidt, Der Massenaustausch in freier Luft und verwandte Erscheinungen, Probleme der kosmischen Physik, Band 7, Hamburg, 1925.
[4] John B. Leighly, Toward a theory of the morphologic significance of turbulence in the flow of water in streams, Univ. California Pub. in Geog., v. 6, No. 1, pp. 1-28, Berkeley, 1932.
[5] M. P. O'Brien, Review of the theory of turbulent flow and its relation to sediment-transportation, Trans. Amer. Geophys. Union, pp. 487-491, 1933.
[6] Robert M. Oaks and Robert T. Knapp, A closed-circuit flume for suspended-load studies, Trans. Amer. Geophys. Union, Part II, p. 525, 1936.
[7] Prandtl - Tietjens, Applied hydro- and aeromechanics, McGraw-Hill Book Company, 1934.
[8] George H. Otto, A modified logarithmic probability graph for the interpretation of mechanical analyses of sediments, J. Sed. Pet., August, 1939.
[9] A. B. Buckley, The influence of silt on the velocity of water flowing in open channels, Min. Proc. of Inst. Civ. Eng., v. 216, p. 183, 1922-1923.
[10] J. E. Christiansen, Distribution of silt in open channels, Trans. Amer. Geophys. Union, Part II, p. 478, 1935.
[11] Hunter Rouse, Experiments on the mechanics of sediment suspension, Proc. Fifth Internat. Cong. Applied Mech., p. 55, 1938.

Soil Conservation Service, Cooperative Laboratory,
California Institute of Technology,
Pasadena, California

DISCUSSION

W. W. RUBEY (United States Geological Survey, Washington, D. C.)--I should like to ask more information on an incidental point mentioned in Mr. Vanoni's paper. One of his lantern-slides shows an increase of about ten per cent in the velocity of flow when 0.15 per cent of sediment is added to clear water. It seems there should be some upper limit to this effect because, presumably at least, the flow must be retarded at very high concentrations of sediment. Have the experiments described by Mr. Vanoni progressed far enough so that this increase of velocity with higher sediment-concentrations can be indicated, even approximately?

A. A. KALINSKE (University of Iowa, Iowa City, Iowa)--This paper presents the results of some very carefully made laboratory experiments on the concentration of suspended material in a rectangular channel. It is probably the most complete series of experiments on suspended-material transportation that has been made and the results will be of inestimable value in permitting a better understanding of the sediment-suspension phenomena in turbulent water.

The writer does not agree entirely with certain statements made in the theoretical analyses and with all of the conclusions. One of the points that was of considerable interest to the writer was the definite conclusion arrived at that the coefficient of momentum-transfer was not equal to that of sediment-transfer. It has, of course, been pointed out by Taylor, Dryden, and others that the exchange of a vector quantity such as momentum is not identical with the exchange of quantities such as heat, mass, etc., under all conditions of turbulent flow. [See paper by Taylor, Transport vorticity and heat through fluids in turbulent motion, Proc. R. Soc., v. 135A, p. 685, 1932.] Experiments seem to indicate that the exchange of momentum and heat in the uniform turbulence created at boundaries is similar, while the exchange in the turbulence formed in the wake of immersed bodies is definitely different. It appears that the exchange of scalar quantities such as heat, water-vapor, or sediment ought to be similar. For instance, unpublished data by the writer show that the exchange or diffusion of immiscible droplets or a chemical solution having the same specific gravity as water is quite similar to the transfer of sediment.

So far as similarity of the exchange of sediment and momentum in an open-water channel is concerned, the writer does not believe any too definite statements can as yet be made. One of the principal reasons for this is the difficulty of calculating the correct value of the momentum-exchange coefficient. All such calculations must be based on some assumption as to the value and distribution of shear. In two-dimensional motion the assumption of linear variation of shear is undoubtedly valid; however, in ordinary open channels where side- and surface-effects are present, together with secondary currents, it is doubtful whether the shear is distributed linearly. The author calculated the value of ϵ_m using the logarithmic velocity-distribution law and assumed a linear shear-variation vertically. The logarithmic velocity-distribution law, though undoubtedly the best theoretical equation for velocity-distribution in wide channels, is not correct near the water-surface, nor, as the author's data (Fig. 7) show, near the bottom. Thus the value of ϵ_m, as calculated in the paper, cannot be considered as the true value of the coefficient of momentum transfer.

The author's remarks regarding the presence or absence of correlation between the turbulent velocity-components are slightly confusing. The correlation that exists when momentum is exchanged in two-dimensional flow is between the vertical component V' and the horizontal fluctuating component U'. The presence or absence of any such correlation has, of course, no relation to the transfer of sediment, since the component U' has nothing to do with keeping sediment in suspension. If the shear is zero the correlation between VI and U' is zero if it is assumed according to Reynolds that $\tau = -\rho\,\overline{U'V'}$. However, this does not mean that ϵ_m is necessarily zero; in fact, the value of ϵ_m calculated from measured velocity-distribution in a circular pipe definitely shows that it has a finite value in the center of the pipe. The value of ϵ_m is zero at the water-surface if the logarithmic velocity-distribution curve is assumed to apply near the surface; however, such is not the case.

The author attempts to explain the observed difference between ϵ_m and ϵ_s for coarse and fine sediments by assuming that the size of the sediment has an effect on the value of the transfer-coefficient. This explanation does not appear to have sufficient physical basis; also, the difference in the absolute concentrations of sediment when coarse and fine sediment was used might be the important factor, and not the size of the sediment.

The fact is mentioned by the author that the flows used were not carrying all the suspended material they were capable of transporting. The flows would have transported all the suspended sediment they were capable of carrying, if the channel-bottom was completely covered with the sand used and the channel was long enough to establish equilibrium. Since it appears from the author's remarks that the channel-bed was not completely covered with the sand being transported, the writer wonders whether this might not have had some effect on the suspended-sediment distribution in the channel cross-section. If the channel-bottom is not uniformly covered with unconsolidated sand it is doubtful whether two-dimensional conditions were approached so far as the suspended-sediment distribution is concerned.

The above remarks and questionings should not be construed as detracting from the value of the paper in any way. The mechanism of suspended-material transport and turbulence is so complex and the interrelationships of the different variables so involved that there is bound to be, in the present state of knowledge, a wide difference of opinion regarding the interpretations of experimental results. These differences will undoubtedly be cleared up as more and more experimental data are available on the fundamental physical mechanisms involved. Our knowledge regarding these mechanisms in the past consisted of hazy, theoretical assumptions; however, our knowledge is gradually becoming clearer and more definite as basic experiments of the type described by the author are carried forth.

C. S. JARVIS (Soil Conservation Service, Washington, D. C.)--It was noticeable in one of the Figures displayed on the screen that the addition of 0.15 per cent caused an almost uniform increase of velocity amounting to approximately ten per cent whether it be taken near the bottom, near the surface, or at intermediate depths. The question now submitted to the author is as follows: "What was the effect due to doubling the sedimentary load from 0.15 to 0.3 per cent by weight of the total discharge? Was the ten per cent increase of velocity maintained, or was it made to give place in favor of something greater or less?"

RATIONAL EQUATION OF RIVER-BED PROFILE

Samuel Shulits
(Presented by G. H. Matthes)

Introduction--River engineering has been faced for many years with the dilemma that, on the one hand, its accumulated experience is sometimes inadequate for reliable prediction of river behavior, while, on the other hand, there has been little attempt at systematic quantitative evaluations to "discover identity in difference"--all the above referring particularly to the form of river-channels, in cross-section, plan, and profile. The purpose of this paper is to review certain principles which afford a rational derivation of the profile of river-beds and to test the results on several American rivers.

Derivation of equation of river-bed profile--As particles of bed-load move downstream, their size or weight is reduced by abrasion or wear, collision, and solution. The most important of these factors is abrasion, for which Sternberg developed a law that has been verified experimentally by Schoklitsch [see 1 of "References" at end of paper]. The reduction in weight of a stone or particle, as it travels downstream, should be proportional to the work done against friction along the bed. If P is the weight of the stone and φ the coefficient of friction, the frictional resistance to motion is at any instant φP. The work against friction in a very short distance dx is $\varphi P dx$. Let dP be the resulting decrease in weight. Then it can be said that

$$- dP = c\varphi P dx \tag{1}$$

in which c is a constant of proportionality. The minus sign indicates that P decreases as x increases--that is, - dP goes with + dx. Integration yields

$$P = P_0 e^{-ax} \tag{2}$$

or

$$\log_{10} P = \log_{10} P_0 - ax \log_{10} e = \log_{10} P_0 - 0.434ax \tag{3}$$

with $c\varphi$ replaced by "a" and $\log_{10} e$ by 0.434. In this, the Sternberg abrasion law, P is the weight of a stone in pounds after traveling a distance of x miles downstream from the starting point where the initial weight was P_0 while e is the base of natural logarithms. The quantity "a" is called the coefficient of abrasion or wear of the bed-load material and represents the loss in weight of a stone weighing one pound after traveling one mile; the units of "a" are pounds per pound per mile or mile^{-1}. It might just as well be called the coefficient of weight decrease, a significance that will be recalled below.

Krumbein [2, p. 579] measured the average pebble-size along the beach at Little Sister Bay, Wisconsin, and found empirically that the size-variation with distance along the beach followed an exponential law like that in equation (2).

Since the bed-slope of a river and the size of bed-load material are known to decrease from source to mouth, it is not far-fetched to assume the slope proportional to the size of bed-load material. Mathematically expressed

$$S = kP_0 e^{-ax} \tag{4}$$

where S is the bed-slope and k is another constant of proportionality. At the starting point where x = 0, $S = S_0$, so that $kP_0 = S_0$ and

$$S = S_0 e^{-ax} \tag{5}$$

or

$$\log_{10} S = \log_{10} S_0 - 0.434ax \tag{6}$$

which is the equation of the slope of river profiles. A more detailed derivation of equations (2) and (5) will be found in reference [3].

$S = S_0 e^{-ax}$ is a rationally deduced formula, based on reasonable or at least plausible assumptions and not on measured data. There is no compulsion for a measured, actual bed-profile to conform to it. But if profiles can be shown to have an equation of this form, the inference must be that equation (5) is reliable and valid. Proof of this will follow below.

Application to practical problems has shown that a slight variation in the form of above slope-distance equation is convenient. It is desirable to let S_0 be the slope at a downstream initial point and to measure x positive upstream from S_0, where x - 0. Equation (5) then becomes

$$S - S_0e^{ax} \tag{7}$$

The simple mathematical transformation need not be given here. Figure 1 is a schematic representation of the significance of the variables for this equation and another to be derived later.

The above formulas are dimensionally correct, so that any consistent system of units may be used. In this paper the following will be the system of units: S in feet per miles, x in miles, and "a" in pounds per pound per mile or $mile^{-1}$.

Validity of $S - S_0e^{ax}$--Equation (7) can be written

$$\log_{10}S - \log_{10}S_0 + ax \log_{10}e \tag{8}$$

whence it is evident that $S - S_0e^{ax}$ should plot as a straight line on semi-logarithmic paper, which is the clue to the proof of its reliability. If the data from an actual river yield a linear relation on semi-logarithmic paper, then $S - S_0e^{ax}$ is justified.

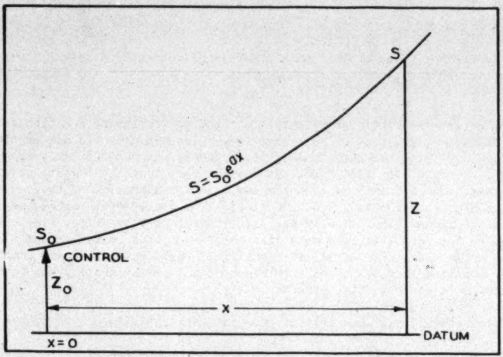


Fig. 1--Variables in bed-slope equation, $S - S_0e^{ax}$

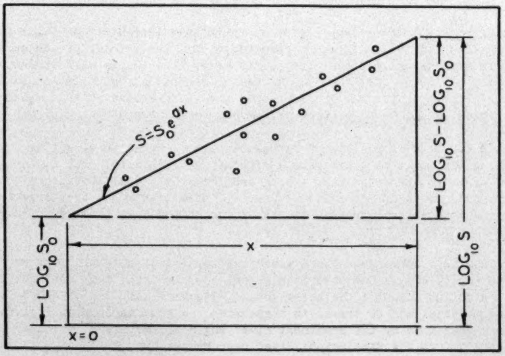


Fig. 2--Semi-logarithmic chart of $S - S_0e^{ax}$

The proof has another important aspect. From (8) can be obtained

$$0.434a = (\log_{10}S - \log_{10}S_0)/x \tag{9}$$

But the right-hand side of the above is the slope of the straight line on semi-logarithmic paper, as Figure 2 shows; and the wear-coefficient, a, is then the slope of the line divided by 0.434 or

$$a = (\log_{10}S - \log_{10}S_0)/0.434x = [\log_{10}(S/S\ )]/0.434x \tag{10}$$

Accordingly, if the wear-coefficient so determined from the plotted data for an actual river corresponds to the kind of material of which the bed-load is known to consist, a second test of validity has been made.

By writing (10) thus

$$\log_{10}(S/S_0) = 0.434ax \tag{11}$$

it can be seen that the logarithm of the ratio of slopes is proportional to the loss in weight suffered by a one-pound stone in traveling x miles, the distance between S_0 and S, for a is the loss in weight of a one-pound stone in a distance of one mile.

The procedure is to break a given profile into a series of connected straight lines, determine the slope of each section and plot this slope against the distance of its midpoint from the starting place.

The Mississippi River was the first one selected to check the foregoing equations. The basic data were taken from the first page of reference [4]. Circumstances did not permit the calculation of an average line from the 1932 thalweg given there. It was initially assumed, for the purpose of this exploratory computation, that the profile made from the lowest low-water reading at each gage (regardless of time) would be an adequate approximation of the bed-profile. With the Fort Jackson, Louisiana, gage as x = 0, the slopes of the different reaches were plotted against the midpoint of the reach (Fig. 3). The calculations extended to Cairo, Illinois, 1,051 miles above Fort Jackson. The points for the main stretch of the river reveal an unmistakable trend, though not necessarily a clearly defined straight line. But, in view of the complexity of the problem, it must be admitted that the results in Figure 3 are really gratifying, for too much should not be expected in these initial efforts.

The evaluation of the overall wear-coefficient from the straight line put in by eye in Figure 3 is

$$a = [\log_{10}(S/S_0)]/0.434x = \log_{10}[(0.403/0.130)]/0.434(700) = 0.00162 \text{ pound per pound per mile} \tag{12}$$

A check was made by using the 1901 low-water profile of the Mississippi River [5], but no appreciable change in the magnitude of the coefficient resulted. Only the points for the main stretch of the river were used in this determination. The points below Baton Rouge were excluded because the 1901 low-water profile [4] shows that the Gulf backwater extends up to Baton Rouge; while the points above Cottonwood Point were also not considered as the river-slopes in this reach are known not to conform to Mississippi River experience, as Figure 3 shows strikingly.

The coefficient thus computed is really not representative of abrasion except in a very loose way; in fact, "abrasion" might be a misleading misnomer in this case. But it can be regarded as a coefficient of weight decrease that is derived from the actual profile, without any implication of the process by which the decrease occurs. In this light, the coefficient might be considered an overall characteristic representative of the morphologic behavior of river-profiles.

The value of 0.00162 mile^{-1} corresponds to a very tough material, slightly less wear-resistant than cast iron [1, p. 354]. Computed from actual profile-data, this coefficient includes the effects of the solids loads of the tributaries. Its smallness may be due to the fineness of the bed-load material and to travel in suspension. A remarkable practical check of this value of 0.00162 has been made by the prominent river engineer, Gerard H. Matthes. He found years ago that pebbles from the Mississippi River near Memphis would scratch the steel blade of his pocket-knife and quite recently, that a piece of gravel would scratch a razor-blade with ordinary hand pressure.

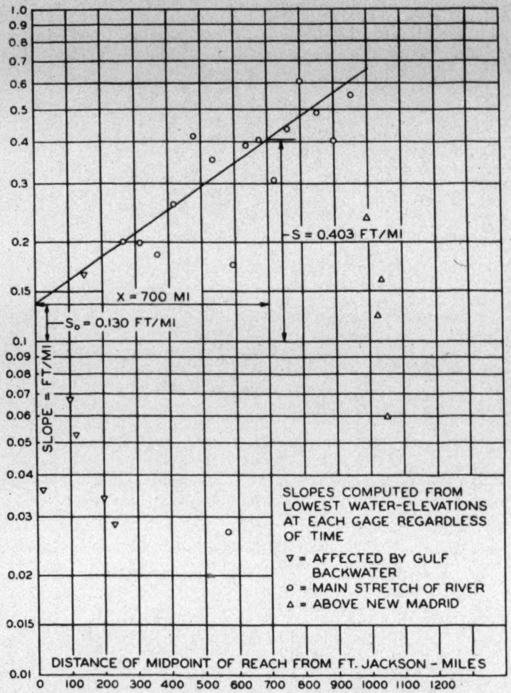


Fig. 3--Variation of low-water slope along Mississippi River; determination of abrasion-coefficient from $S = S_0 e^{ax}$

The Ohio River from Cairo, Illinois, to Pittsburgh, Pennsylvania, a distance of 980 miles, was next treated in the same way. The profile-data were obtained from the lowest low-water gage-readings, regardless of time [6]. The plot of slope against distance is given in Figure 4, which also exhibits an encouraging trend and regularity. At Mile 748 solid rock is known to exist, which may explain the scattering of some of the data above this locality.

The value of 0.00293 mile^{-1} or pounds per pound per mile is obtained for the wear-coefficient for the Ohio River from the slope of the straight line put in by eye in Figure 4. This would be a material as resistant as a mineral somewhere between porphyry and silicious shale [1, p. 354], which Mr. Matthes believes corresponds well with Ohio River material. This means that Mississippi River gravel is about twice as tough as Ohio gravel, a fact borne out by practical observation.

A slope-distance chart, like Figure 3 or 4, of the Colorado River from Boulder Dam to the International boundary-line (about 350 miles) demonstrated a similar trend and yielded a value of the wear-coefficient very close to that for quartz--which is what would be expected for the material of the Colorado River.

With data given by Krumbein [2, p. 586] it was found that the slope of the surface of the alluvial fan at the mouth of San Antonio Canyon (Cucamonga, California, topographic map) conforms

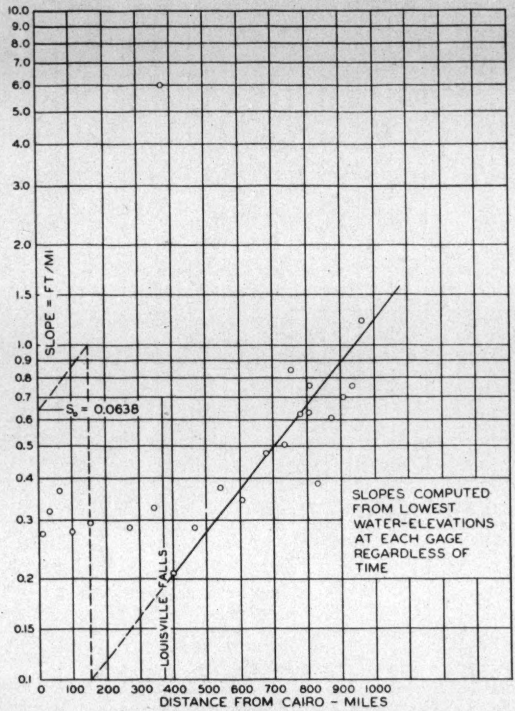


Fig. 4--Variation of low-water slope along Ohio River

to $S = S_0e^{ax}$ very closely. No attempt was made to compute the wear-coefficient.

The conclusion is that the Mississippi, Ohio, and Colorado rivers and an alluvial fan offer corroborative evidence of the validity of the rational equation of $S = S_0e^{ax}$ for the slopes of rivers: First, because the plot of the profile-data on a semi-logarithmic chart exhibits an overall linear trend well within the limits of accuracy of such morphologic data; and second, because the wear-coefficient derived from the profile agrees astonishingly well with the nature of the bed-load or bed-material of the rivers.

Another form of the profile-equation--A variation of the bed-profile equation, in terms of elevation and horizontal distance, can be derived from $S = S_0e^{ax}$. Let z_0 be the elevation at $x = 0$ where the slope is S_0, and let z be the elevation at any point x where the slope is S (Fig. 1). If dz is the change in elevation in a very short horizontal distance dx, then the slope $S = dz/dx$ and equation (7) becomes

$$S = dz/dx = S_0e^{ax} \qquad (13)$$

or

$$dz = S_0e^{ax}\,dx \qquad (14)$$

which can be integrated to

$$z - z_0 = (S_0/a)\ (e^{ax} - 1) \tag{15}$$

If the elevation is taken through the origin, $z_0 = 0$ and equation (15) can be simplified to

$$z = (S_0/a)\ (e^{ax} - 1) \tag{16}$$

It must be remembered that equations (15) and (16) are merely derivations from $S = S_0e^{ax}$ and not independent formulas. But they are more directly applicable to profiles and therefore more interesting to the river engineer. Their significance and utility will be discussed.

This different form of equation is not suited to an easy check of the basic principles, though a profile can be computed if the wear-coefficient, a, is known. However, Gandolfo [7, p. 80] tried equation (15) on the San Juan River in Argentina and found agreement of practical adequacy between actual and computed values of the river-profile in an 11.5-mile stretch of the river for which comparisons could be made. The coefficient was computed from the mechanical composition curves of the bed-material in a manner similar to that suggested by Schoklitsch [1, p. 357], which space requirements prevent from explaining here. Gandolfo's investigation is therefore another verification of the general method.

The profiles of the Middle Rhine (Mittelrhein), Maas, Mur, and Enns rivers in Europe also conform to equation (15) [8].

The semi-logarithmic slope-distance plots (Figs. 3 and 4), not being common engineering practice, are not very illuminating and the physical significance is not easily visualized. Furthermore, the scattering of the points on these diagrams might induce doubt and the fitting of a straight line to the data by inspection might be questioned. For this reason the elevation-distance equations (15) or (16) are quite reassuring in the diagrams they yield, for they show that the straight-line approximation and the resulting value of the wear-coefficient give good elevation-profiles. The gradient of the line on the slope-distance chart cannot be changed too much and still be sensibly acceptable; but the small possible shifts of the line would not alter the computed elevation-profile appreciably and the calculated profile is well within reasonable limits of accuracy. To illustrate this, the profiles of the Mississippi and Ohio rivers will be determined from equation (16).

For rivers all the variables in equation (16) are easily determinable except the wear-coefficient a. As explained elsewhere [1, 3, 9, 10], it is not a constant for a given rock or bed-load material: It increases with the one-fourth power of the particle-velocity, is proportional to the diameter of the material over which the particle rolls, and depends on the pebble-shape. That a should vary for different parts of a river is evident, the reduction in weight per pound per mile decreasing downstream in general. This difficulty is circumvented for river-engineering purposes by computing an overall coefficient for the entire stretch of river under consideration; the shorter the reach, the more representative the coefficient. Yet as will be seen presently, this method yields useful results even for a 1,000-mile continuous stretch of river.

Where it is not practicable to work from profile-data, a value of the wear-coefficient can be estimated for the type of mineral in the river from experimentally determined values [1, pp. 352-354].

The choice of S_0, the slope at the starting point, $x = 0$, is slightly troublesome. It is best to determine S_0 from the semi-logarithmic chart (Figs. 2, 3, and 4). The intersection with $x = 0$ of the straight line through the plotted points yields a good value of S_0 for the purpose.

With $a = 0.00162$ mile^{-1} from equation (12) and $S_0 = 0.130$ foot per mile from Figure 3, equation (16) gives for the elevation-profile of the Mississippi River

$$z = (0.130/0.00162)(e^{0.00162x} - 1) = 80.2(e^{0.00162x} - 1) \tag{17}$$

Values of e^{ax} can be secured from any handbook [11]. The profile given by equation (17) was computed and fitted by inspection to the 1901 low-water profile (Fig. 5). The calculations were made with $x = 0$ at Fort Jackson which is affected by Gulf backwater. The 1901 profile in reference [4] shows that the Gulf effect extends up to Baton Rouge, 209 miles from Fort Jackson. The best visual fit of equation (17) was found to be the portion of the calculated curve from $x = 203$ miles upward, if begun on the actual profile at Mile 230. The equation of the fitted profile would then be

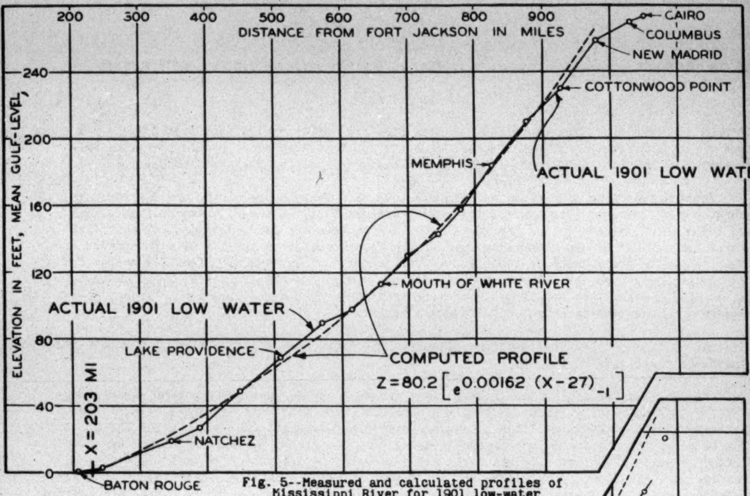


Fig. 5--Measured and calculated profiles of Mississippi River for 1901 low-water

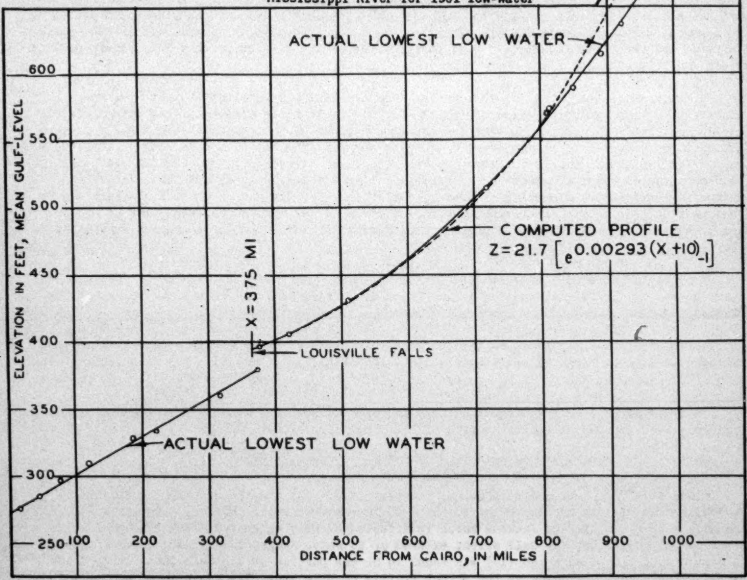


Fig. 6--Measured and calculated profiles of Ohio River

$$z = 80.2\ [e^{0.00162(x-27)} - 1] \qquad (18)$$

A closer fit might have been obtained by least-square methods. The maximum deviation of the computed profile from the 1901 Mississippi low-water line below Cottonwood Point is only about six feet. The rather marked divergence above Cottonwood Point is due to the fact that the portion of the river above it was not utilized in the determination of the wear-coefficient from Figure 3.

The satisfactoriness of the Mississippi River profiles in Figure 5 is no added proof of the basic tenets of this article. Figure 5 merely affords a better idea of the closeness of fit, of the utility of the method and of the effect of a variation in the wear-coefficient.

For the Ohio River, with $a = 0.00293$ mile^{-1} and $S_0 = 0.0638$ foot per mile from Figure 4, the derived profile is given by

$$z = 21.7\ [e^{0.00293(x+10)} - 1] \qquad (19)$$

shown in Figure 6. At Mile 800 the Little Kanawa River enters the Ohio River, which may explain the divergence of the two lines above this point. Both Figures 4 and 6 depict strikingly the change in regimen at the Louisville Falls.

General remarks on applicability and limitations--The rather good results with the Mississippi and Ohio River profiles must not be judged too optimistically or too enthusiastically. Plots of other streams do not always show the regularity of these examples, but in many cases careful inspection of the stream gives a physical interpretation of seeming discrepancies: Rock outcrops, dams, flashy tributaries, debris-cones, local overloading of the stream-capacity for solids transport, etc., may disturb the wear-phenomena on which the ideas in this paper are predicated. In such instances the profile can sometimes be approximated by a series of lines calculated with locally varying coefficients. Steep headwaters in mountainous regions may not fit the framework since collision more than wear might be the predominating agent.

Conclusions--The Mississippi, Ohio, and San Juan rivers, several rivers in Europe, and an alluvial fan substantiate the premise of this paper, that wear-phenomena offer a rational approach to river-bed-profile morphology. The inference is that the bed-load plays a very important role in forming the river-channel.

Tho caution is indicated, the rational instrument offered here for the analysis of river-profiles gives a practical means for expressing the vertical shape of a river-bed so that the morphologic effect of man-made measures can be studied. The usefulness of $S = S_0e^{ax}$ and $z = (S_0/a)(e^{ax} - 1)$ lies in the fact that they formulate the equilibrium-profile, that which will prevail ultimately or after complete morphologic development. Hence, if the regimen of a river is altered by regulation, a practical prediction of the final form can be ventured, with more rational basis for the estimate than has been the case hitherto.

A fanciful possibility is the establishment of a relation between an overall wear-coefficient like "a" and the watershed geology that would permit fluvial or physiographic predictions in a manner akin to the use of flood-formulas--certainly an accuracy equal to the dubious one of this common hydrologic tool should be attainable.

Acknowledgments--The author is grateful to General M. C. Tyler and Gerard H. Matthes for a critical perusal of the paper and many valuable suggestions. Bruno Rigoni assisted in the calculations and plotted the river-data.

References

[1] A. Schoklitsch, Über die Verkleinerung der Geschiebe in Flussläufen, Proc. Acad. Sci. Vienna, Math.-nat. sci. class, sect. IIa, v. 142, No. 8, pp. 343-366, 1933.

[2] W. C. Krumbein, Sediments and exponential curves, J. Geol., v. 45, No. 6, pp. 576-601, 1937.

[3] S. Shulits, Fluvial morphology in terms of slope, abrasion, and bed-load, Trans. Amer. Geophys. Union, pp. 440-444, 1936.

[4] Mississippi River Commission, Maps of the Mississippi River, Cairo, Illinois, to the Gulf of Mexico, Louisiana, 7th ed., revised January 1939.

[5] Mississippi River Commission, Highest and lowest annual stages of the Mississippi River and principal tributaries to 1937; 1939.

[6] Chief of Engineers, The Ohio River--charts, drawings and description of features affecting navigation, etc., pp. 323-324, 1935.

[7] J. S. Gandolfo, Estudio de la evolucion fluvial que determina el endicamiento del Rio San Juan, Publications of the Faculty of Physico-Mathematical Sciences, third series, v. 2, special publications, La Plata, Argentina, pp. 1-21, 1940.
[8] A. Schoklitsch, Hydraulic structures, Amer. Soc. Mech. Eng., v. 1, p. 153, 1937.
[9] A. Schoklitsch, Geschiebebewegung in Flüssen und an Stauwerken, Julius Springer, Vienna, pp. 3-7, 1936.
[10] A. Schoklitsch, Stauraumverlandung und Kolkabwehr, Julius Springer, Vienna, pp. 4-17, 1935.
[11] O. Eshbach, Handbook of Engineering Fundamentals, John Wiley and Sons, New York, pp. 1-103, 1936.

War Department,
U. S. Waterways Experiment Station,
Vicksburg, Mississippi

DISCUSSION

W. W. RUBEY (U. S. Geological Survey, Washington, D. C.)--I am very much interested in Mr. Shulits' paper. Geologists, quite as much as hydraulic engineers, are concerned with this subject of the longitudinal profiles of streams. In some ways, they are even more concerned because in correlating remnants of old stream-terraces or in attempting to detect earth-deformation since some terrace was formed, they must be able to make reasonable guesses about the original undisturbed profiles of the ancient streams.

Anyone who has ever plotted stream-profiles has probably felt convinced that certain broad principles must underlie and explain the systematic smoothness of these curves. As a result, a wide variety of equations, thought to fit the profiles of particular streams, has been suggested. These have ranged from a simple parabola based on a uniform increase of discharge downstream to double logarithmic graphs based on nothing more or less than good "fits".

The exponential equation discussed by Mr. Shulits is similar to, if not identical with, equations found by Sternberg, Putzinger, Schoklitsch, and Gandolfo to fit the profiles of certain rivers in other continents. The fact that the lower Mississippi, the lower Ohio, and a portion of the Colorado River fit this equation very well is the contribution of this paper.

The author calls this a rational equation of stream-profiles, by which I take it he makes the customary distinction between empirical equations, on the one hand, and analytical equations, based on deduction from known principles, on the other. But I believe it is a mistake to consider this exponential equation as anything other than strictly empirical. In saying this I certainly do not mean in any way to belittle the importance of empirical equations, because it is largely by means of them that the new principles of any science become established. Nevertheless, the distinction between the two is important to keep in mind.

The basis for considering this exponential equation of stream-profiles as analytical is that it involves Sternberg's law of the rate of wear of bed-load material with distance of stream travel. Now even if we grant, for purposes of this argument, that Sternberg's law is valid for all important types of bed-load abrasion (which, strictly speaking, it is not), it still does not follow that this stream-profile equation can be deduced therefrom.

Schoklitsch observed empirically that the slope of many European rivers tends to vary as the size of their bed-load materials. This is really a surprising observation and one not at all easy to explain. In fact, it seems definitely to contradict other well-established relationships. All experience to date, so far as I am aware, indicates that the size of material moved by a stream depends not solely upon the slope but also and in a complex manner upon other factors such as the velocity and hydraulic mean depth of the stream. Furthermore, laboratory experiments, such as those of G. K. Gilbert, demonstrate conclusively, to my way of thinking, that the graded slope or the slope of equilibrium established by a stream depends not solely upon the size of debris making up the bed, but also and very definitely upon other variables such as the discharge of water, the load or amount per unit-time of sediment being transported, the shape of channel cross-section, and the degree of sorting of the sediment. Consequently, to find that the slope of a stream varies directly as the third power of bed-load diameters, as Schoklitsch and Shulits have done, is a surprising fact to be explained only by the existence of complex and as yet unformulated interrelationships among the many other variables.

For these reasons, it seems clear that the exponential equation of stream-profiles must be judged on its own merits as a strictly empirical equation. As such it suffers somewhat in comparison with other equations because it is more cumbersome to use and more difficult to test graphically. It certainly is important to compare the fit of this and other equations on the same streams and Mr. Shulits deserves very real thanks for having made these laborious tests of the exponential equation against the data on certain American streams.

SAMUEL SHULITS (War Department, U. S. Waterways Experiment Station, Vicksburg, Mississippi; communicated)--Mr. Rubey's comment on empirical and rational equations is interesting. In its broadest sense, empiricism is a philosophical theory attributing the origin of all knowledge to experience. In this light, everything except divinely inspired knowledge would be empirical, even the kinetic theory of gases which was built up painfully from various experimental observations--unless one wishes to consider the possibility of "pure reason."

If characteristic parameters of a natural phenomenon are measured and a mathematical equation or formula determined subsequently that fits the measurements (usually plotted), the equation or formula is said to be empirical--this is the author's understanding of an empirical equation. The form of the equation is not predicted: It is found by trial and error or statistical methods. While numerical values can be obtained from the empirical equation, no general conclusions can be derived from it, no general investigations based on it. On the other hand, if from accumulated knowledge (= experience) certain broad principles, concepts, or tenets are drawn, these then given a quantitative garb and used to rationalize a quantitatively clothed concept called a formula or equation, the latter may be conceded to be rational--this is the author's understanding of a rational equation. The form of the equation is predicted, but may not be true and may not fit measured data. Numerical values can also be obtained from such an equation; general conclusions can be derived from it and general investigations based on it.

In arriving at the profile-equations, no measured data are used. By expressing certain ideas, beliefs, or natural phenomena in mathematical form, an equation is obtained. It is then said that actual slope-measurements should conform to this equation, but the actual slope-data are not the basis of the equation. This is the definitive point: The data for the Mississippi and Ohio rivers and the San Antonio alluvial fan were not plotted first and the best curve fitted by empirical methods; instead, the equation was predicted from very general premises, not dependent on specific instances, and finally it was shown that the river- and fan-data could be put into the proposed framework. The steps in building the equation are expressible thus: (1) Bed-load material wears or decreases in size as it travels downstream; (2) the slope decreases downstream; (3) there is a broad correlation between (1) and (2). Most engineers explain relation (3) to themselves or visualize it in different ways, but it is acceptable. Schoklitsch claims that this step is justifiable by observation. In mathematical terms these three steps are: (1) $P = P_0e^{-ax}$; (2) S is proportional to x in some way; (3) $S = kP_0e^{-ax} = S_0e^{-ax}$

Mr. Rubey believes that bed-load experiments invalidate or are inconsistent with the profile-equation. It is true that the assumption of the slope being proportional to the weight of the bed-load material is equivalent to assuming it to vary "as the third power of bed-load diameters." But since the examples in the paper conform to the equation implying the third power, it must be inferred that the third-power property holds for the cited rivers. The reason for not using the diameters is that no one knows what diameter would be representative of the bed-load material, despite a plethora of literature on size-analysis and interpretation. The seeming inconsistency between the profile-equation and bed-load formula is due to incompleteness of our knowledge of the various interlocking factors. It is then necessary to be satisfied temporarily with correlations that do not take into account all possible factors; in fact, the engineer is at a loss to say what many of these factors might be. The slope-equation is to the bed-load formula probably what a backwater-equation is to a velocity-formula. Some day the interrelation will be known and susceptible to analysis. To point out what are at present the imponderables of fluvial morphology is of value, but there is still too little basis for rigorous refutation of this or that.

Since the proposed slope-equation fits eight streams in different parts of the world and since it is not derived from these streams but independently of them, the equation merits further consideration. It has been the author's experience that every apparent divergence from the equation is explainable in a simple way that is compatible with a simple framework of fluvial morphology. It is certainly not desired to convey that the question is settled once and for all, since the problem is too complicated, as Mr. Rubey points out. But until our horizon of knowledge is expanded, this slope-equation deserves attention. The author asks that engineers and geologists try this analytic method on rivers familiar to them and communicate to him their findings, favorable or adverse.

BASIC ASPECTS OF STREAM-MEANDERS

Gerard H. Matthes

This paper sets forth certain fundamentals relating to the dynamics of meandering streams derived from extended observations made by the writer on streams ranging in size from mere rivulets to as large as the Lower Mississippi River. These observations were supplemented by others made on undistorted as well as on distorted experimental models. The nomenclature and definitions herein were selected by reference to what appeared to be the best usage found in the literature on the subject.

The term meander is here applied to any letter-S channel-pattern, fashioned in alluvial materials, which is free to shift its location and adjust its shape as part of a migratory movement of the channel as a whole down the valley. The term is held to be strictly appropriate only when the channel-migration affects both bends and intervening straight reaches, and is in the nature of a fairly consistent and more or less continuous process in which banks are torn down and others are built up through a transfer of materials. Mere tortuosity, or crooked channel-alinements, are not classed as meanders. When the materials composing the alluvium are fairly uniform as to grain-sizes and erodability, migratory processes of true meander-type produce definite sinuous patterns and are noteworthy for the consistency with which the channel-dimensions are reproduced. The popular belief that every bend of a meandering channel is destined to build out into a great loop which eventually cuts itself off, is not borne out by the writer's observations. Undue lengthening of a bend appears to be a deformity or abnormality rather than a normal characteristic of stream-meanders.

When we speak of stream-meanders, the term stream takes on a restricted meaning. Strictly, we are concerned only with a channel-characteristic. This may manifest itself over a stretch that is short relative to the total length of the river, or may repeat itself at intervals along the river's course wherever the conditions are favorable. Meandering is not therefore confined to the lower reaches of large rivers. At one extreme is its occurrence at high altitudes in mountain streams whose beds often are composed of coarse gravel or even small boulders; at the other extreme figure the small low-water channels that wander in the wide dry beds of some of our large western streams. The dynamic aspects in all cases are essentially similar. Meandering takes place alike in aggrading, in degrading and in "poised" channels, poised being used here to denote streams having no apparent tendency to either aggrade or degrade, but not synonymously with the morphological term "graded".

Not less than five variables appear to be basic factors of river-meandering. These variables operate in conjunction and are not readily studied singly, except through experimental processes of elimination. Listed in order of their apparent importance they are:

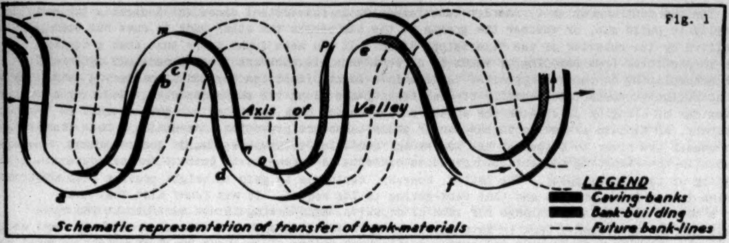
(a) Valley-slope--This is the overall slope of the land-surface traversed by the stream and is measured down the axis of the valley as determined by the general course of the stream. In the case of undistorted experimental models, it is represented by the initial slope given to the bed of materials in which the model stream is permitted to meander at will fashioning its own channel and gradients. A change in valley-slope always produces a change in the meander-pattern, assuming the next three factors to remain unchanged. This basic aspect is readily observable in Nature.

(b) Bed-load--This is that part of the sediment-load which drags along the bottom by rolling and saltation, or which, in the case of streams transporting very fine materials, takes the form of a dense mass moving in semi-suspension just above the bed. Next to the valley-slope, the bed-load is the most important basic factor affecting the meander-pattern. Its composition as well as its quantity-rate of movement materially affect the shape of the meanders.

(c) Discharge--This concerns the seasonal stream-flow variations as represented in the average yearly discharge hydrograph. In experimental work definite assumptions are necessary as regards proportioning the duration of the low, medium, andhigh stages. The importance of this will be appreciated because of the close relation that exists between rate of discharge and rate of bed-load movement in natural streams.

(d) Bed-resistance--This is controlled by the character of the materials composing the alluvium, more particularly by its resistance to erosion. Grain-sizes, specific gravity, cohesion, and the roughness of the channel-lining are important factors. Grain-sizes may range all the way from cobblestones in headwater alluvium to fine sands and silts in the lower reaches of large rivers, but a cobblestone alluvium produces as definite a meander-pattern as does one composed of sand.

(3) Transverse oscillation--This relates to changes in the slope of the water-surface at right-angles to the axis of flow. In a river having a regular meander-pattern the water-surface



Schematic representation of transfer of bank-materials

during all but very low stages is level across only at the crossings. It may be likened to the warped surface of a sinuous modern highway, with pronounced superelevation at the concave shores. These surface-oscillations are evidence that the fluid prism of a stream possesses a definite swing or pendulum-action, initiated normally at bends, but produced or influenced also by shoals, protruding banks, obstructions to flow, and wind-action. In natural channels, whether straight or curved, these oscillations are ever present when bed-load is in motion, and this appears to be true of small rivulets and laboratory models.

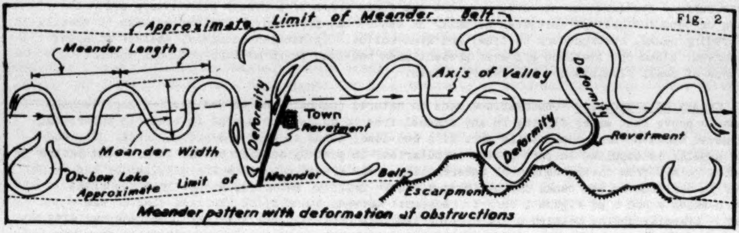
Causes of meandering--Observations made on natural channels and on undistorted experimental channels prove that water flowing in any channel free to adjust its course in erodable materials, and whose sediment-load consists in part of a bed-load, tends to take a sinuous course. The bed-load usually is supplied in part by the tributaries, in part by erosion of the banks. The latter results mainly from caving caused by undercutting. The eroded materials are utilized by the river in building up new banks farther down stream. Briefly, materials eroded from the right bank between a and b of Figure 1 tend to redeposit between c and d, on the same side of the river. Likewise caving between m and n along the left bank supplies materials for bank-building between o and p. In these transfers relatively small portions of the eroded materials show any tendency to cross the channel. Some of the bank-materials that cave into the river at m may angle their way across the current towards the right bank and come to rest before reaching d. In the straight reaches the bed-load travels over the full width of the bed and mixing of right-bank and left-bank materials with bed-load coming from points farther upstream takes place. However, the bulk of the transfers from bank-caving to bank-building proceed along the same side of the river. Materials carried past d continue their journey to the next bend and come to rest between e and f, and some of this material may travel even to points farther downstream before coming to rest. The orderliness of the migratory movement and hence the similarity in the shape of the individual meanders depend upon the regularity with which these transfers take place, and this regularity in turn depends largely upon the degree of uniformity of the bank-materials. A meandering channel may be said to possess a stable channel when its migration is so orderly that channel-dimensions, hydraulic gradients, and the consonance between transverse oscillations and channel-pattern are being preserved despite its constant shifting.

If a river flowing in an erodable channel could coordinate velocity with bed-resistance by simply adjusting its width, then, theoretically it could maintain a straight, but wide and shallow, channel down the axis of the valley. Its hydraulic gradients then would equal the valley-slope and its bed-load would travel over the full width of a very flat bed. Extraordinary as such a condition would be, it is in rare instances met with in nature in a small way, as for instance in channels descending debris cones and alluvial fans. Such channels, however, are unstable and usually short-lived.

In ordinary streams having tough, resistant banks, the bed-load collects in bars or shoals which tend to alternate in position along opposite shores and which force the low-water channel to take a sinuous course, often causing it to swing alternately from bank to bank. When the bars transplant themselves down the river during high stages, the low-water channel tends to shift with them. Migration of this kind as a rule is an extremely slow process requiring accurate hydrographic surveys at yearly or greater intervals for determination. In a meandering channel this action is basically similar, but becomes greatly intensified through the yielding character of the banks which add greatly to the volume of the bed-load. From this results a constant tendency towards redeposition. This results in salients which encroach on the channel, forcing the current against the bank opposite and causing the latter to cave into the river.

The old controversy as to whether bank-recession is the initial cause which permits the bar opposite to build out, or whether the growth of the bar causes the other bank to cave has been clarified by the behavior of the Mississippi River. It has been found there that when a caving bank is prevented from receding by means of a revetment this does not prevent bed-load materials from accumulating on the bar opposite. Available evidence indicates that in a meandering channel accretion proceeds independently of what takes place along the shore opposite. Reducing a convex bar by dredging alleviates the attack on the caving bank opposite, but this at most is temporary, as renewed accretion on the convex shore cannot be prevented. Revetting a bank therefore causes the river to deepen as the convex bar continues to advance towards the revetment. Eventually the resulting constriction produces currents so strong as to prevent further outbuilding of the convex point. The latter, however, continues to gain in height proving that accretion is a primary process and that bank-caving is its sequel. It was found also that whenever a convex bar fails to enlarge for lack of deposits, bank-caving is not manifest at the opposite shore. The concave bank in such cases merely recedes through attritional erosion by the current, a process which is so slow, compared with bank-caving, as to have small significance in the morphology of a truly meandering stream.

Fig. 2



Meander pattern with deformation at obstructions

Sediment in suspension--Sediment in suspension does not appear to be a basic factor in meandering channels. At most it affects channel-roughness but slightly, because siltation of the channel-lining is not as effective in a meandering channel undergoing frequent change as it is in channels possessing firm banks.

Axis of current--Misconceptions regarding the attack of swift currents on concave banks appear to be wide-spread. It is true that during ordinary stages and particularly falling-flood stages the thread of greatest velocity is close to the concave bank. However, during rising-flood stages the thread of maximum velocity tends to shift away from the outside of the curve towards the center of the channel, and during a bank-full stage is usually found to be a considerable distance away from the concave bank. In the Mississippi River during over-bank stages, as in a great flood, the water along the concave bank is relatively slow and steamboat pilots navigating upstream choose this as the path of easiest ascent. The thread of greatest velocity then scours across the convex bars and tends to straighten out and follow the axis of the valley, approximating the line of maximum or valley-slope. This phenomenon is not peculiar to the Mississippi but can be observed in any meadow brook when in flood. It is only on the falling stages that the convex bars receive their greatest deposits and build out, causing the swifter water to hug the concave shore and undermine its toe. Bank-caving therefore is principally a falling-flood-stage phenomenon.

Helicoidal flow--This takes place in distorted models, and in channels which are deep relative to their width. Its well-known occurrence there has created the impression that helicoidal flow also takes place in meandering rivers. The writer's studies indicate that streams engaged in meandering in alluvial deposits are notoriously shallow in cross-section and are devoid of helicoidal motion. In fact, helicoidal flow is almost physically impossible of occurrence in them. No evidence of helicoidal motion has been found in the meandering portion of the Mississippi River, nor in lesser meandering streams examined by the writer.

Hydraulic gradient--The hydraulic gradient of a meandering channel is a succession of modifications of the valley-slope into gradients adapted to the transportation of both water and sediment under the peculiar bed-resistance and variable-flow conditions existing. An equilibrium is thus maintained through the ability of the river to borrow bed-load materials from bed and banks as needed to offset any tendency towards over-acceleration during rising stages, or to dispose of bed-load material as its transporting capacity wanes on the falling stages, the net result being a channel which, at low water, always exhibits very nearly the same cross-sectional dimensions.

Investigation proves that the hydraulic gradients in these processes undergo complete cycles, changing with stage and with rising, falling, and stationary river-conditions. Briefly, the so-called pools or deep-bend sections have notoriously flat surfaces during low stages, but gain rapidly in slope during rising stages, and possess the steepest slopes during flood-flow. Conversely, the straight-channel portions, commonly called the cross-over reaches, have their steepest slopes during low stages and their flattest slopes during high stages. At about a bank-full stage this succession of diverse slopes approaches a nearly uniform hydraulic gradient throughout.

Additional to the cycle of slope-changes, here described, the axis of the current and therefore the effective hydraulic length of the channel shortens and lengthens as previously mentioned. As length is a function of slope, this aspect needs to be taken into account in hydraulic computations, the high-water axis being materially shorter than the low-water axis. It will be clear that slope-values of meandering streams for use in formulas of the Chezy type must be approached with great caution.

Deformed meanders--Major departures from the meander-pattern (Fig. 2) are usually attributable to interference with the methodical transfer of the bank-materials, causing the river to change its mode of migration by seeking a path of less resistance. Large-scale interference results principally from three natural causes: (a) Accelerated erosion of banks composed of soft or highly erodable alluvium which cave or crumble at a rate faster than the generally prevailing rate; (b) resistance to bank-caving due to the presence of lenses of compacted silts or clays which have acquired a greater degree of consolidation than that of the surrounding alluvium; (c) contacts with non-alluvial formations, as for instance glacial debris, or foothill materials which take the form of talus or solid rock. Tough silt- and clay-beds are typical of many alluvial deposits and owe their origin commonly to sedimentation in ox-bow lakes and abandoned secondary channels. Only the finer suspended silt-particles carried overland by flood-waters settle out in such lakes and channels. In their compacted state the resulting silt-bodies may be of such magnitude as to become important barriers to the normal shifting of a meandering river. In the case of the Lower Mississippi, meandering is often impeded by the presence of silt- and clay-deposits of this origin. The alluvium laid down by a river if not homogeneous in character wields a marked influence in promoting distortions of the meander-pattern.

Incised meanders--River-meanders which have become rigidly entrenched into a hard formation through some process of accelerated erosion, are not free to migrate and do not obey the laws herein described. The subject is mentioned here in an effort to dispel the rather common belief that incised meanders afford a useful comparison with meanders in erodable materials. Some instances have come to the writer's attention, notably the Brazos River above Mineral Wells, Texas, where the evidences are obvious that the meanders were created by an earlier stream differing appreciably in size and general characteristics from the present one. Different climatic conditions affecting rainfall, differences in sediment-load, and even a difference in size of drainage-area may readily account for this. In cases of this kind incised meanders are not likely to be representative of or fit the stream now flowing in them, and the latter should be classed geomorphologically as a "misfit" stream.

Channel-width--Channel-width, which has been used to some extent as a function of the meander-pattern, is not believed to be a basic factor. Empirical relations based on it thus far have failed to yield consistent results. Although width is related in some measure to each of the five basic factors above described, it evidently is not truly representative of the many patterns that are produced by combining different values of these five variables.

Function of transverse oscillations--Aside from theoretical considerations, little headway has been made in arriving at a practical working knowledge of the function of the transverse oscillations of the water-surface. It is probable that these oscillations constitute an important factor in maintaining the orderliness of the meander-pattern, and by the same token become a disturbing factor whenever the orderly migration of the meanders is interfered with and an irregular channel-alignment results.

One broad aspect appears to be clearly indicated, namely, that a meandering channel, unlike a headwater stream which carves its channel along the path of least resistance, normally builds and refashions its bed and banks out of the materials which it transports, and in these processes it cannot be said to follow the path of least resistance. Whenever, due to local obstruction, a meandering channel is deflected into a less resistant direction its orderly process of channel-migration is interfered with and extended loops result. It appears illogical to place bank-recession by caving in the same category of stream-erosion phenomena as bank-corrasion such as occurs in eroding headwater streams.

Much remains to be learned concerning the exact manner in which the transfers of bank-materials take place in a meandering channel. The dynamics of these processes are under investigation by the Mississippi River Commission, both in the river and at the United States Waterways Experiment Station.

Mississippi River Commission,
Vicksburg, Mississippi

DISCUSSION

GEORGE W. HOWARD (Corps of Engineers, Fort Belvoir, Virginia)--The assembly of the fundamentals of the mechanics of meandering streams is a worthy contribution, and the manner in which Mr. Matthes has presented the information is of great value.

The listing of the variable basic factors in order of their importance is of particular interest. There would seem, however, to be an interdependence such that the separation into various grades of importance would be extremely difficult.

With regard to the geomorphology of any area that would result in a meandering stream, the "valley-slope" must necessarily be considered first, since the geologic processes resulting in the arrangements for the future formation of any stream-valley would necessarily antedate other influences. Then the hydrology of the particular area must be considered with the resultant effect on the rainfall-intensities governing the discharge. Dependent on these factors is the bed-load, which has undoubtedly a great effect on the meander-pattern.

While the above facts are applicable to an earlier period in the history of the stream than those presented for observations on alluvial streams, the allusions are made for the purpose of showing how closely related all of these variables are.

Two interesting mathematical treatises on the subject have appeared recently [see 1 and 2 of "References" at end of paper], but when one considers the limited data available, the results of years of observations by one person assume even greater importance.

Observations by the writer [3] have confirmed the remarks of the author in regard to the manner in which eroded materials are utilized by a stream in building up the new banks below the point at which caving occurs; that is, "the bulk of the transfers from bank-caving to bank-building proceed along the same side of the river." The stream on which most of the writer's observations have been made can in no way be classed as a river, but the phenomena described by Mr. Matthes are generally in evidence.

It was noted with interest and satisfaction that no mention was made of the effect of the Earth's rotation upon lateral erosion. This phenomenon, treated by Babinet, in 1849, and von Baer, in 1866, is generally known as "Baer's Law." It has been discussed at length by Gilbert [4], Eakin [5], and others. The writer believes that, while this phenomenon is one that is present in all large streams, it is for the most part offset by local conditions, and has no effect on small streams; therefore, the effect of the Earth's rotation upon lateral erosion cannot be considered in a presentation of the fundamentals of meandering.

References

[1] Relationship between meander belts, distance between meanders on axis of stream, width and discharge of rivers on flood plains and of incised rivers, Tech. Note No. 12, Central Irrigation and Hydrodynamic Res. Sta., Poona, India, June 1938.

[2] H. Chatley, The theory of meandering, Engineering, v. 149, No. 3385, pp. 628-629, 1940.

[3] Unpublished results of research course entitled "Stream meanders," Geo. Washington Univ., Dept. Geol., 1941.

[4] G. K. Gilbert, The diversion of water courses by the rotation of the Earth, Bull. Phil. Soc. Washington, v. 7, pp. 21-25, 1885.

[5] H. M. Eakin, The influence of the Earth's rotation upon the lateral erosion of streams, J. Geol., v. 18, No. 5, pp. 435-447.

CHANNEL-STORAGE AND DISCHARGE-RELATIONS IN THE LOWER OHIO RIVER VALLEY

B. R. Gilcrest and L. E. Marsh
(Presented by B. R. Gilcrest)

Introduction--Recent studies made in the Ohio River Division Office of the United States Engineer Department have involved the analysis of storage- and discharge-relations and have resulted in development of approximate flood-routing procedure for the Lower Ohio River Valley where the situation is complicated by the confluence of the Ohio River with the Mississippi, Tennessee, Cumberland, and Wabash rivers. In this paper are presented the results obtained from study of the following reaches:

(1) Reach terminating at the confluence of the Ohio and Mississippi rivers at Cairo, Illinois, and extending from Thebes, Illinois, on the Mississippi River, 44 miles above Cairo Point, and from Golconda, Illinois, on the Ohio River, 78 miles above Cairo Point.

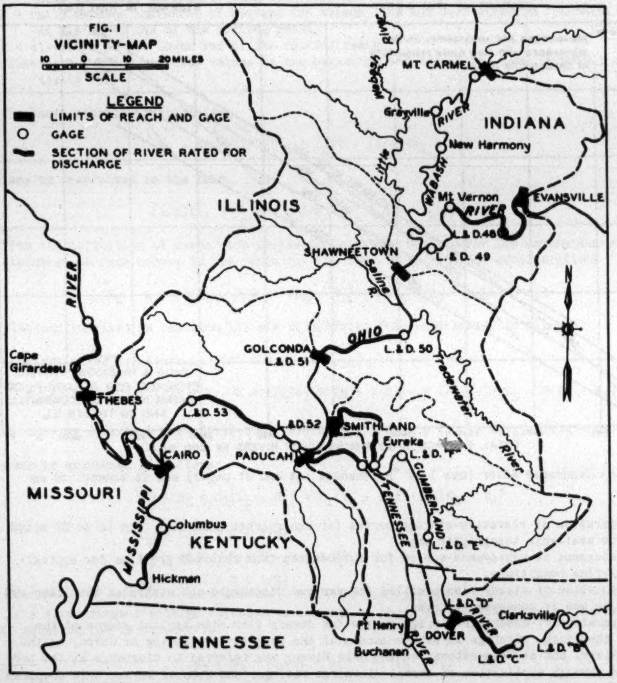


FIG. I
VICINITY-MAP
10 0 10 20 MILES
SCALE
LEGEND
LIMITS OF REACH AND GAGE
GAGE
SECTION OF RIVER RATED FOR DISCHARGE
Wabash River
Little Wabash River
MT. CARMEL
Grayville
INDIANA
New Harmony
Mt. Vernon
RIVER
EVANSVILLE
L.& D. 48
ILLINOIS
SHAWNEETOWN
Saline R.
L. & D. 49
RIVER
Cape Girardeau
THEBES
GOLCONDA L.& D. 51
OHIO
L.& D. 50
Tradewater River
L.& D. 53
L.& D. 52
SMITHLAND
Eureka
L.& D. "F"
CAIRO
PADUCAH
MISSOURI
MISSISSIPPI
Columbus
KENTUCKY
TENNESSEE
CUMBERLAND
L.& D. "E"
Hickman
L.& D. "D"
Clarksville
Ft. Henry
DOVER
RIVER
L.& D. "B"
TENNESSEE
Buchanan
RIVER
L.& D. "C"

(2) Reach terminating at Shawneetown, Illinois, on the Ohio River and extending from Mt. Carmel, Illinois, on the Wabash River, 95 miles from Shawneetown, and from Evansville, Indiana, on the Ohio River, 66 miles from Shawneetown.

(3) Reach of the Cumberland River from Dover, Tennessee, to its mouth, a distance of 88 miles.

The map of Figure 1 shows the extent of the reaches under investigation, the location of river-gages, and discharge-rating stations utilized in the studies.

Procedure for development of storage-discharge relations--The procedure followed in developing basic discharge-storage relations for each reach is essentially the same as that used in

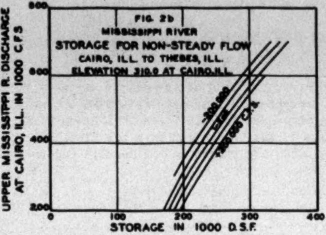


FIG. 2b
MISSISSIPPI RIVER
STORAGE FOR NON-STEADY FLOW
CAIRO, ILL. TO THEBES, ILL.
ELEVATION 310.0 AT CAIRO, ILL.

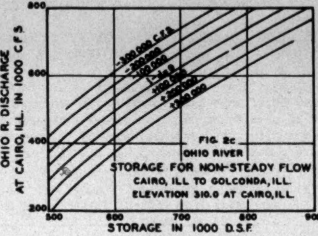


FIG. 2c
OHIO RIVER
STORAGE FOR NON-STEADY FLOW
CAIRO, ILL TO GOLCONDA, ILL.
ELEVATION 310.0 AT CAIRO, ILL.

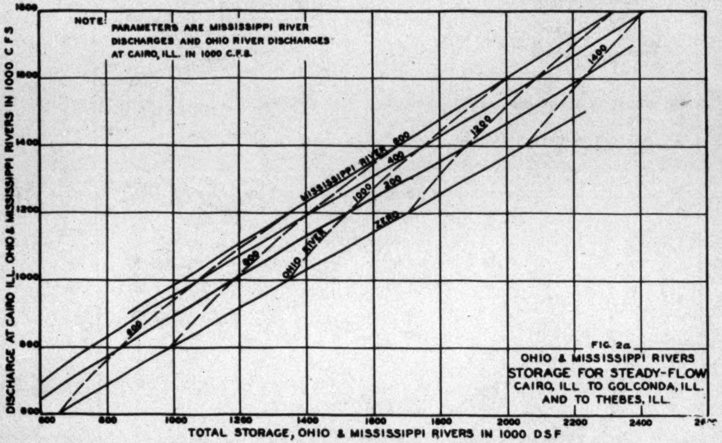


FIG. 2a
OHIO & MISSISSIPPI RIVERS
STORAGE FOR STEADY-FLOW
CAIRO, ILL TO GOLCONDA, ILL.
AND TO THEBES, ILL.

NOTE: PARAMETERS ARE MISSISSIPPI RIVER DISCHARGES AND OHIO RIVER DISCHARGES AT CAIRO, ILL. IN 1000 C.F.S.

studies on the Tennessee River [see 1 of "References" at end of paper] and is summarized as follows:

(1) Preparation of elevation-storage curves for sub-reaches generally from 15 to 25 miles in length from available topographic maps.

(2) Development of conveyance-curves for sub-reaches from observed profiles for approximately steady-flow conditions.

(3) Computation of steady-flow profiles for various discharges and stages at the lower end of the reach by use of conveyance-curves.

(4) Preparation of discharge-storage curves for steady flow with various stages at the lower end of the reach. Storage in both branches of the reaches terminating at Cairo, on the Mississippi River, and at Shawneetown, on the Ohio River, was referred to discharge at the terminal station through application of normal discharge-ratings, and sets of curves were prepared for both reaches to show discharge in each of two branches as a parameter. Because of the absence of a reasonable approximation to a fixed relation between stage and discharge at the mouth of the Cumberland River, discharge-storage curves for the Cumberland River reach were plotted with stage at the mouth as a parameter. Storage-curves for steady-flow conditions in each of the three reaches under study are shown on Figures 2(a), 9, and 10.

(5) Computation of profiles for non-steady flow for various stages at the lower end of each reach with discharge assumed to vary in the upstream direction in proportion to distance from the terminal station.

(6) Preparation of discharge-storage curves for non-steady flow with difference between inflow and outflow as parameters for selected stages at the lower end of each reach. Typical sets of storage curves for non-steady flow are shown on Figures 2(b) and 2(c).

Development of basic relations--Analysis of discharge-storage relations developed in study of the Lower Ohio River Valley has been made primarily with a view to application of what may be termed the "Coefficient-method" of routing which has been described by G. T. McCarthy [2]. Notations and definitions applicable to the development of basic relations used in the study are as follows.

i = inflow in cfs
d = outflow in cfs
S = storage in dsf
t = time in days
M = storage-factor equal to $(S + dt/2)$
K = ratio between corresponding increments of storage and discharge for steady flow
N = ratio between wedge-storage and the corresponding difference between inflow and outflow with discharge assumed to vary with distance
P = ratio between increment of storage for steady flow and corresponding increment of stage at the lower end of the routing reach
E = elevation at the lower end of the routing reach
Subscripts 1 and 2 indicate values at the beginning and end of the time-interval, respectively

The basic storage-equation is

$$S_2 - S_1 = (1/2)(i_1 + i_2)t - (1/2)(d_1 + d_2)t \tag{1}$$

which may be rearranged in the form

$$(1/2)(i_1 + i_2)t - d_1t/2 + S_1 = S_2 + d_2t/2 = M \tag{2}$$

From the definition of terms, the following relations apply under the assumption of straight-line discharge-storage curves in the range for the time-interval under consideration:

$$S_2 - S_1 = K(d_2 - d_1) + P(E_2 - E_1) + N(i_2 - d_2) - N(i_1 - d_1) \tag{3}$$

The relations involved in equation (3) are illustrated diagrammatically in Figure 7.

Combination of equations (1) and (3) gives

$$d_2 = [1/(K - N + t/2)][(K - N - t/2)d_1 + (N + t/2)i_1 + (t/2 - N)i_2 - P(E_2 - E_1)]$$

or

$$d_2 - d_1 = [1/(K - N + t/2)][-td_1 + ti_1 + (N - t/2)i_1 + (t/2 - N)i_2 - P(E_2 - E_1)] \tag{4}$$

which may be expressed as follows:

$$d_2 - d_1 = C_0(i_1 - d_1) + C_1(i_2 - i_1) - C_2(E_2 - E_1) \tag{5}$$

when

$$C_0 = t/(K - N + t/2)$$
$$C_1 = (t/2 - N)/(K - N + t/2)$$
$$C_2 = P/(K - N + t/2)$$

If a fixed stage-discharge relation is assumed to apply at the lower end of the routing reach, equation (5) is reduced to

$$d_2 - d_1 = C_0(i_1 - d_1) + C_1(i_2 - i_1) \tag{6}$$

in which C_0 and C_1 have the same values as in equation (5).

If t is taken equal to 2N, equation (4) is simplified to take the form

$$d_2 - d_1 = (t/K)(i_1 - d_1) - (P/K)(E_2 - E_1) \tag{7}$$

Assumption of a fixed stage-discharge relation at the lower end of the routing reach permits reduction of equation (7) to the form

$$d_2 - d_1 = (t/K)(i_1 - d_1) \tag{8}$$

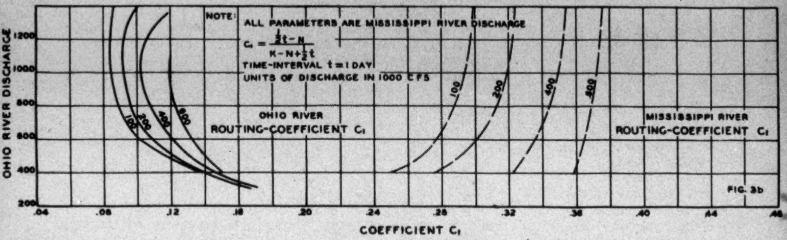


FIG. 3b

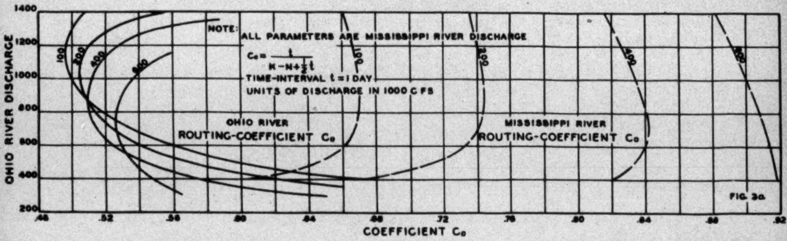
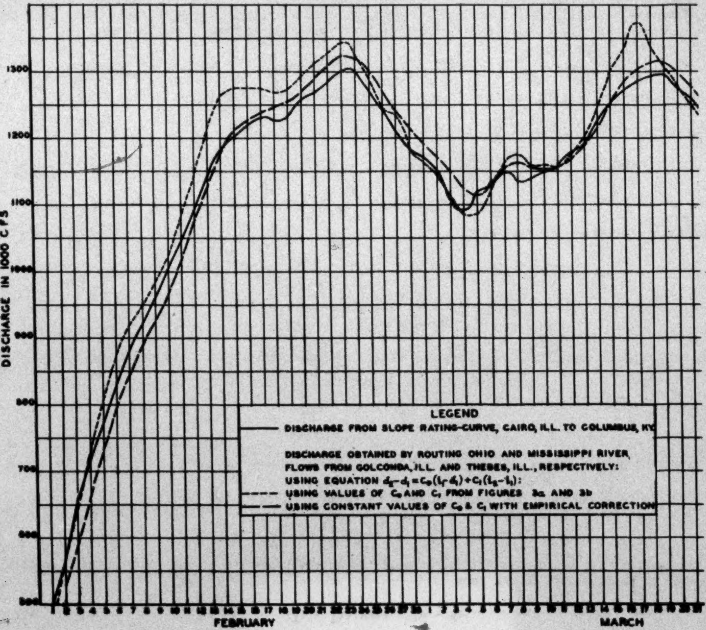


FIG. 3a



LEGEND

DISCHARGE FROM SLOPE RATING-CURVE, CAIRO, ILL. TO COLUMBUS, KY.

DISCHARGE OBTAINED BY ROUTING OHIO AND MISSISSIPPI RIVER FLOWS FROM GOLCONDA, ILL. AND THEBES, ILL., RESPECTIVELY:

USING EQUATION $d_2 - d_1 = C_0(i_1 - d_1) + C_1(i_2 - i_1)$:

USING VALUES OF C_0 AND C_1 FROM FIGURES 3a AND 3b

USING CONSTANT VALUES OF C_0 & C_1 WITH EMPIRICAL CORRECTION

It is to be noted that equations (7) and (8) may be applied for a time-interval not equal to 2N on the assumption of linear variation in discharge for the time-interval assumed.

The objective in development of discharge-storage relations for reaches involving two branches was to put the data in a form adapted to use in routing procedure in which inflows for each branch would be routed separately and the computed results combined to give the discharge at the lower end of the reach. The storage-curves for steady-flow conditions shown on Figures 2(a) and 9 conform with the requirements for such use as may be demonstrated by reference to the diagram on Figure 8. In the example shown on Figure 8, the inflow for the right branch in the time-interval under consideration is first routed through storage in both branches, with discharge in the left branch assumed to be steady and equal to the routed value obtained for that branch at the end of the previous time-interval. In this procedure, correction is made for wedge storage in the right branch, and the volume of storage accounted for in this step is that between profiles jac and hfe. Within a limited range of discharge, the values of wedge storage denoted by triangles aij and fgh may be regarded as equal, and the storage accounted for in the first step may be considered equivalent to that between profiles iac and gfe. The next step is the routing of inflow for the left branch through storage in both branches, with discharge in the right branch assumed to be steady and equal to the final discharge obtained in the first step, and with correction being made for wedge storage in the left branch. The operations of this step account for storage between profiles gfd and okl, which may be considered equivalent to the storage between profiles gfe and okm.

Ohio-Mississippi River reach--First analysis and application of discharge-storage relations in routing procedure was made for the use of equation (6) in the Ohio-Mississippi reach which terminates at Cairo and extends from Thebes, on the Mississippi, and from Golconda, on the Ohio River. The curves of Figure 2(a) were first analyzed for slope in various sections to obtain values of K, the ratio between increment of storage and corresponding increment of discharge,

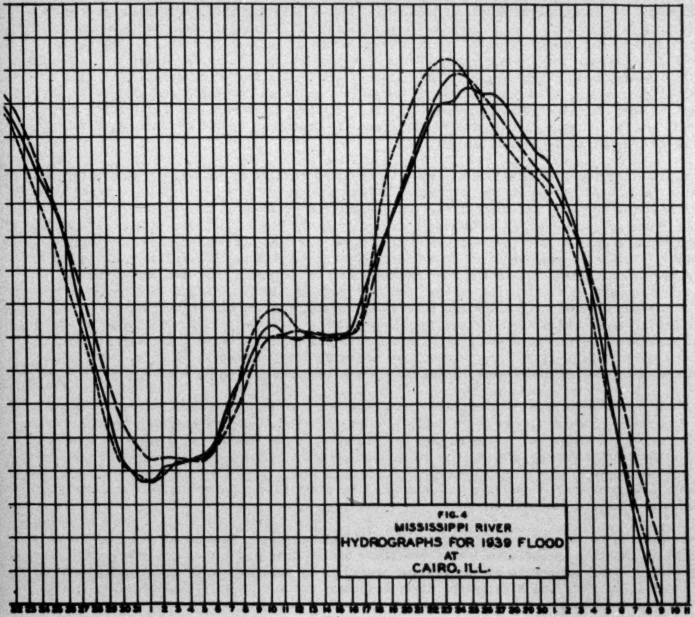


FIG. 4
MISSISSIPPI RIVER
HYDROGRAPHS FOR 1939 FLOOD
AT
CAIRO, ILL.

Table 1--Example of routing at confluence of Ohio and Mississippi rivers, Golconda-Thebes-Cairo Reach

Item	Calendar day, March, 1939							
	10		11		12		13	
	Ohio	Miss.	Ohio	Miss.	Ohio	Miss.	Ohio	Miss.
Inflow i_1	951	191	987	205	1006	203	1012	228
Inflow i_2	987	205	1006	203	1012	228	1009	294
Change in inflow $(i_2 - i_1)$	+36	+14	+19	- 2	+ 6	+25	- 3	+66
Coefficient C_1 from Fig. 3-b	0.09	0.32	0.09	0.32	0.09	0.32	0.09	0.32
$C_1(i_2 - i_1)$	+ 4	+ 4	+ 2	- 1	+ 1	+ 8	0	+21
Discharge d_1	966	194	962	196	977	201	993	210
$(i_1 - d_1)$	-15	- 3	+25	+ 9	+29	+ 2	+19	+18
Coefficient C_0 from Fig. 3-a	0.51	0.74	0.51	0.74	0.51	0.74	0.51	0.74
$C_0(i_1 - d_1)$	- 8	- 2	+13	+ 6	+15	+ 1	+10	+13
$(d_2 - d_1) = C_0(i_1 - d_1) + C_1(i_2 - i_1)$	- 4	+ 2	+15	+ 5	+16	+ 9	+10	+34
Discharge d_2	962	196	977	201	993	210	1003	244
Total discharge d_2	1158		1178		1203		1247	

Note: All flows are in units of 1,000 c f s; values of C_0 and C_1 obtained from Figures 3-a and 3-b.

for steady flow in both the Ohio and Mississippi River branches of the routing reach. A set of working curves was plotted for each branch to show values of K in terms of discharge in the branch under consideration, with discharge in the other branch as a parameter. Storage-curves for non-steady flow, examples of which are shown on Figures 2(b) and 2(c), were used to prepare similar sets of curves to show variation in the coefficient N, which is a measure of wedge storage in terms of difference between instantaneous values of inflow and outflow. The values shown for K and N by the four sets of curves were then applied to obtain the curves in Figures 3(a) and 3(b) which show values of the coefficients C_0 and C_1 for use in equation (6) with a time-interval of one day. The fixed stage-discharge rating for Cairo, which was applied in the development of discharge-storage curves, was utilized to make the conversions required to give values of C_0 and C_1 in terms of Ohio River discharge with discharge in the Mississippi River as a parameter as presented in Figures 3(a) and 3(b).

The flood of February to May 1939 was used to test the results of routing for the Golconda-Thebes-Cairo reach terminating at the confluence of the Ohio and Mississippi rivers. There were three crests during the 1939 flood which had peak-discharges of about 1,300,000 cfs in the Mississippi River below Cairo, the peak-contributions from the Mississippi above Cairo in the three rises being about 160,000 cfs, 440,000 cfs, and 580,000 cfs. Inflow for the Mississippi River branch of the reach was developed from a slope-rating for the Cape Girardeau range which is eight miles above Thebes, the rating for the range at Thebes not having been sufficiently well developed for use in the studies at the time they were initiated. Inflow for the Ohio River branch was obtained by combining discharge from slope-ratings for the Ohio River at Golconda, the Cumberland River at its mouth, and the Tennessee River at its mouth, with discharge from intermediate ungaged areas as estimated from rainfall with allowance for base flow at the rate of one cfs per square mile. Runoff from rainfall was estimated by application of 24-hour-distribution values of 10-30-30-15-15 per cent, using 80 per cent of rainfall as effective.

Results of routing for the Golconda-Thebes-Cairo reach for the 1939 flood-period are shown on Figure 4, on which routed discharge at Cairo is compared with discharge obtained from a slope-rating referred to the Cairo and Columbus gages and based upon the results of discharge-measurements made at Hickman, Kentucky, during the 1939 flood-period.

In Table 1 is presented a sample of computations involved in obtaining routed discharge at Cairo through application of equation (6).

Further studies of the Golconda and Thebes-Cairo reach have been made to ascertain whether results could be improved by modification of procedure and whether simplified procedure could be used to advantage. Simplification of the routing procedure by application of equation (8) with values of (t/K) in the Ohio and Mississippi River branches, for t = 1 day, as shown by curves in Figure 5, was found to produce a routed hydrograph which differed little from that obtained in the first study. The simplified procedure gave outflow which was greater on the rising side of

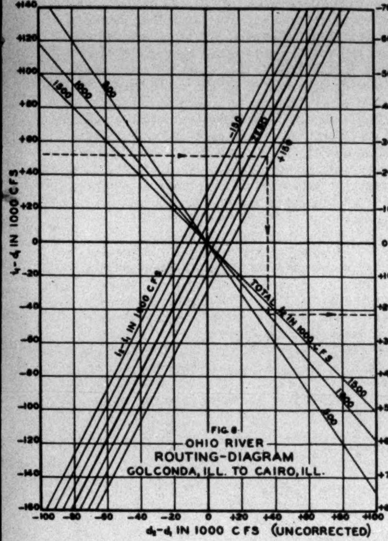


FIG 6
OHIO RIVER
ROUTING-DIAGRAM
GOLCONDA, ILL. TO CAIRO, ILL.

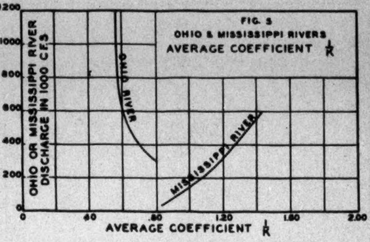


FIG. 5
OHIO & MISSISSIPPI RIVERS
AVERAGE COEFFICIENT $\frac{1}{R}$

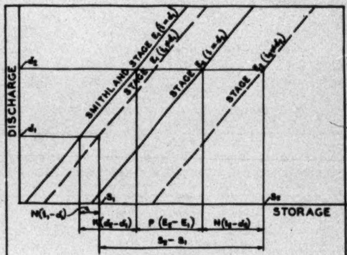


FIG. 7
DIAGRAM TO ILLUSTRATE EQUATION
$S_2-S_1=K(d_2-d_1)+P(E_2-E_1)+N(i_2-d_2)-N(i_1-d_1)$

the hydrograph, and less on the falling side, the difference being generally less than 5,000 cfs. Peak-values differed by 10,000 cfs or less. The application of equation (8) also was modified by using a time-interval of 0.5 day, instead of 1.0 day, which compares with a maximum value of 2N equal to 0.25 day in the Mississippi branch and equal to 0.68 day in the Ohio River branch. No improvement in the form of the routed hydrograph was obtained with the shorter time-interval, differences between results for 0.5 day and 1.0 day being no more than 2,000 to 3,000 cfs, in general.

The results of routing in the Ohio-Mississippi River reach by the methods described above were not considered particularly satisfactory even with allowance for normal discrepancies in discharge-ratings and errors in estimating runoff from ungaged areas. It was believed that most of the error resulted from failure to account for effect of variable relation between stage and discharge at Cairo upon discharge-storage relations. A method of correction which appears to offer possibilities for practical application was developed on an empirical basis for use in connection with equation (6). Diagrammatic illustration of the correction applicable for routing Ohio River flows is shown by Figure 6 which provides a graphical method for solution of the equation $d_2 - d_1 = C_0(i_1 - d_1) + C_1(i_2 - i_1)$ and for making correction intended to account for effect of variable stage-discharge relations at Cairo. Basically, the correction involves the assumption that deviation from the normal rating curve at Cairo is proportional to tne rate of change in discharge, and that the deviation, in per cent of total discharge, is constant. The correction was considered to be measurable in terms of combined Ohio and Mississippi River inflow. As shown by the comparison of final and uncorrected $(d_2 - d_1)$ values on the diagram of Figure 6, the correction for a final $(d_2 - d_1)$ of 50,000 cfs amounts to about 3.3 per cent of the inflow. A diagram incorporating the same correction-curves was prepared for use in routing Mississippi River inflows. Constant values of C_0 and C_1 were applied for use in testing the routing with the empirical correction, although analysis of the discharge-storage curves showed considerable variation in the values, as indicated by Figures 3(a) and 3(b). The selected values of C_0 and C_1 for time-interval of one day, with corresponding values of K and N are as follows:

River	C_0	C_1	K	N
Ohio	0.51	0.103	1.75	0.30
Mississippi	0.76	0.32	0.85	0.08

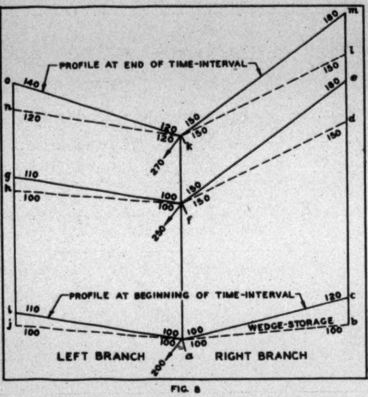


FIG. 8

DIAGRAM TO ILLUSTRATE DISCHARGE-STORAGE RELATIONS AT THE CONFLUENCE OF TWO STREAMS

The hydrograph of discharge at Cairo obtained by routing with the empirical correction is shown on Figure 4. It is apparent that the form of the routed hydrograph is materially improved in the upper range of discharge by application of the correction. The matter of correction to account for effects of variable stage-discharge relations at Cairo is considered to be worthy of further investigation and it is believed that a solution may be obtained through analytical approach, if a suitable correlation between rate of change in stage and deviation from the normal discharge rating at Cairo can be developed.

Ohio-Wabash River reach--Investigation of the reach terminating at Shawneetown, on the Ohio River, and extending from Evansville, on the Ohio, and from Mt. Carmel, on the Wabash, has been limited to the development of discharge-storage relations for steady flow, as shown by the curves on Figure 9. The data shown by Figure 9 were obtained by reference to a fixed stage-discharge relation for the Ohio River at Shawneetown which was established from backwater computations beginning at Cairo and based upon the following conditions:

(1) Fixed stage-discharge relation at the confluence of the Ohio and Mississippi rivers at Cairo

(2) Steady discharge of 200,000 cfs from the Mississippi River above Cairo

(3) Discharge of 100,000 cfs from the Tennessee River and from the Cumberland River.

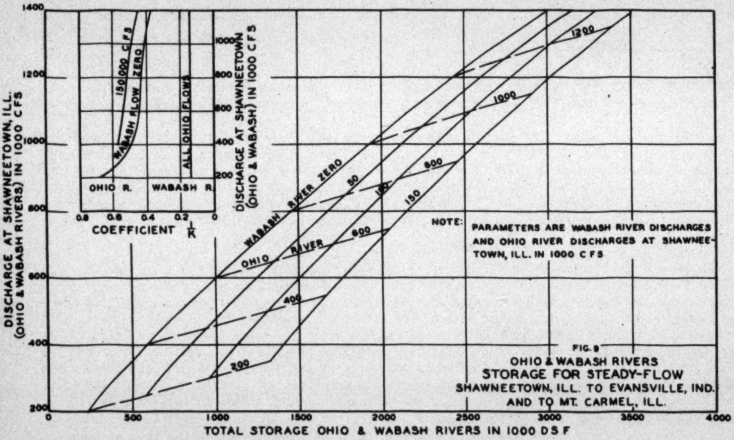
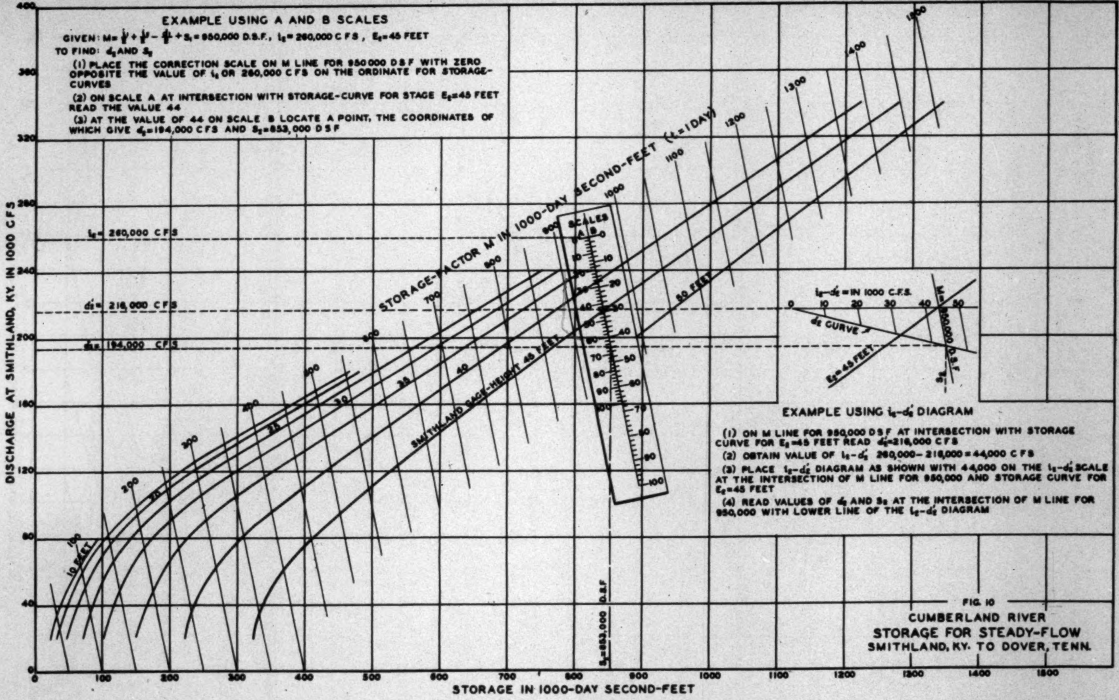


FIG. 9

OHIO & WABASH RIVERS
STORAGE FOR STEADY-FLOW
SHAWNEETOWN, ILL. TO EVANSVILLE, IND. AND TO MT. CARMEL, ILL.

Application of equation (8) in the routing of the 1939 flood through the Evansville-Mt. Carmel-Shawneetown reach, using a time-interval of one day, gave results of about the same order of accuracy as obtained for the reach terminating at Cairo, the routed discharge being compared with discharge at Shawneetown from a slope-rating based upon gages at Shawneetown and at Dam 49. The slope-rating for Shawneetown was established from backwater computations with some adjustment



EXAMPLE USING A AND B SCALES

GIVEN: $M=\frac{i_1}{2}+\frac{i_2}{2}-\frac{d_1}{2}+S_1$ = 950,000 D.S.F., i_2= 260,000 C F S , E_2=45 FEET

TO FIND: d_2 AND S_2

(1) PLACE THE CORRECTION SCALE ON M LINE FOR 950 000 D S F WITH ZERO OPPOSITE THE VALUE OF i_2 OR 260,000 C F S ON THE ORDINATE FOR STORAGE-CURVES

(2) ON SCALE A AT INTERSECTION WITH STORAGE-CURVE FOR STAGE E_2=45 FEET READ THE VALUE 44

(3) AT THE VALUE OF 44 ON SCALE B LOCATE A POINT, THE COORDINATES OF WHICH GIVE d_2=194,000 C F S AND S_2=853,000 D S F

EXAMPLE USING i_2-d_2' DIAGRAM

(1) ON M LINE FOR 950,000 D S F AT INTERSECTION WITH STORAGE CURVE FOR E_2=45 FEET READ d_2'=216,000 C F S

(2) OBTAIN VALUE OF i_2-d_2' 260,000 − 216,000 = 44,000 C F S

(3) PLACE i_2-d_2' DIAGRAM AS SHOWN WITH 44,000 ON THE i_2-d_2' SCALE AT THE INTERSECTION OF M LINE FOR 950,000 AND STORAGE CURVE FOR E_2=45 FEET

(4) READ VALUES OF d_2 AND S_2 AT THE INTERSECTION OF M LINE FOR 950,000 WITH LOWER LINE OF THE i_2-d_2' DIAGRAM

FIG. 10

CUMBERLAND RIVER
STORAGE FOR STEADY-FLOW
SMITHLAND, KY. TO DOVER, TENN.

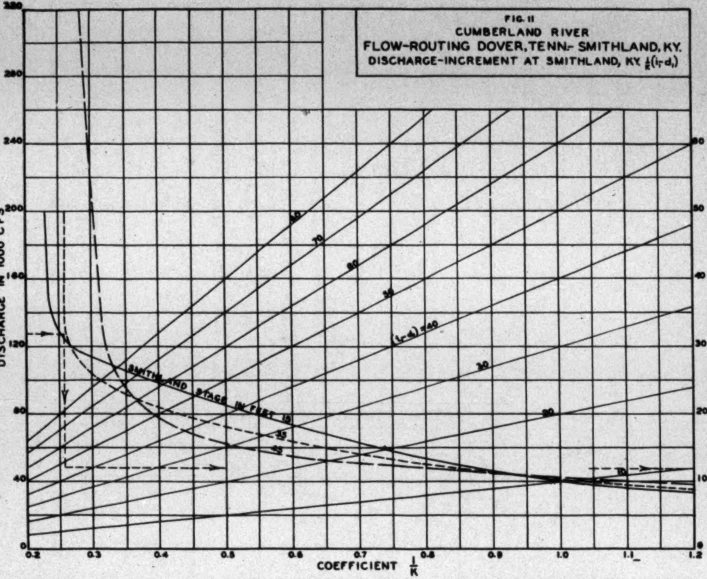


FIG. 11
CUMBERLAND RIVER
FLOW-ROUTING DOVER, TENN.- SMITHLAND, KY.
DISCHARGE-INCREMENT AT SMITHLAND, KY. $\frac{1}{K}(i_1-d_1)$

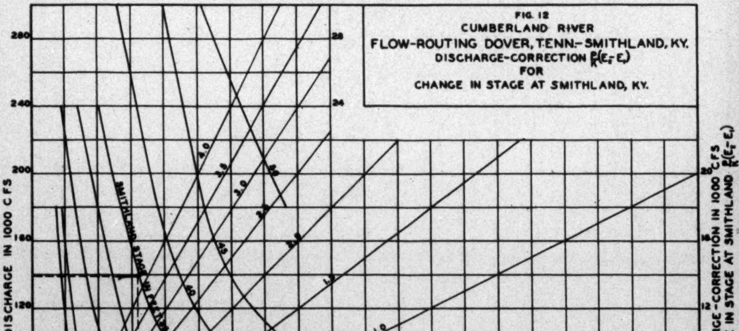


FIG. 12
CUMBERLAND RIVER
FLOW-ROUTING DOVER, TENN.- SMITHLAND, KY.
DISCHARGE-CORRECTION $\frac{P}{K}(E_2-E_1)$
FOR
CHANGE IN STAGE AT SMITHLAND, KY.

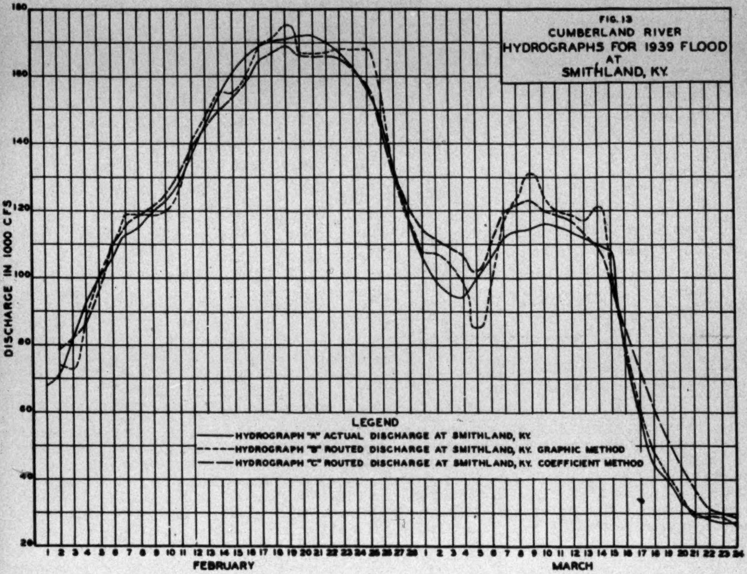


FIG. 13
CUMBERLAND RIVER
HYDROGRAPHS FOR 1939 FLOOD
AT
SMITHLAND, KY.

to secure proper comparison with total volume of flow obtained from the rating for Golconda during the 1939 flood-period.

Lower Cumberland River--Studies of the Cumberland River reach extending from Smithland at its mouth to Dover, 88 miles upstream, required a somewhat different method of approach because of the wide variation in stage at Smithland for given discharges from the Cumberland River. The results of studies for this reach are presented to illustrate methods of solution of the storage-equation in cases requiring correction for change of stage at the lower end of the reach independent of discharge. The situation in this reach is comparable to that for a reservoir controlled by crest-gates, and it is believed that procedure developed in study of the Lower Cumberland may find application in connection with operation of such reservoirs.

Discharge-storage curves for steady-flow conditions as developed for the Cumberland River between Dover and its mouth are shown on Figure 10. Stage at Smithland, at the lower end of the reach, is shown as a parameter on these curves. Lines for various values of the "storage-factor", M, superimposed on the storage-curves, satisfy the requirement of equation (2) for a time-interval of one day, thus making M equal to $(S + d/2)$. The M-lines are used in a routing procedure which is essentially an application of a method developed by I. H. Steinberg [3].

The graphic solution for wedge storage, illustrated by the examples given on Figure 10, is based upon the fact that the spread between parametric (i-d)-curves as developed for the Cumberland River in the same form as shown on Figures 2(b) and 2(c), measured along the M-lines (time-interval of one day) was found to be practically the same proportion of difference between inflow and outflow throughout the full range of discharge and stage. As may be seen by examination of the AB-scale shown on Figure 10, the correction for wedge storage, measured along the M-lines, is equal to about one-third of the difference between inflow and outflow in terms of values on the discharge-ordinate of the storage-curves.

The (i-d')-diagram on Figure 10 is presented mainly to indicate possible means for handling a variable correction for wedge storage. If, for example, it were found that the wedge-storage

Table 2--Example of coefficient-routing, Cumberland River, Dover-Smithland Reach

Item	Calendar day, February, 1939				
	9	10	11	12	13
Stage at Smithland, E_1	31.4	32.9	34.3	35.4	36.3
Discharge d_1	121	125	131	139	145
Inflow i_1	150	164	174	174	172
$(i_1 - d_1)$	+29	+39	+43	+35	+27
$(1/K)(i_1 - d_1)$ from Fig. 11	+ 8	+10	+11	+ 9	+ 7
d'_2	129	135	142	148	152
Stage at Smithland, E_2	32.9	34.3	35.4	36.3	36.8
Stage-increment, $(E_2 - E_1)$	+ 1.5	+ 1.4	+ 1.1	+ 0.9	+ 0.5
Mean stage, $[(E_2 + E_1)/2]$	32.1	33.6	34.8	35.9	36.5
$(P/K)(E_2 - E_1)$ from Fig. 12	+ 4	+ 4	+ 3	+ 3	+ 2
$(d_2 - d_1) = [(1/K)(i_1 - d_1) - (P/K)(E_2 - E_1)]$	+ 4	+ 6	+ 8	+ 6	+ 5
d_2	125	131	139	145	150

Note: All flows are in units of 1,000 c f s.

correction varied appreciably only with stage at the lower end of the reach, the d_2-curve in the (i-d')-diagram could be replaced by a family of curves to give the proper correction for different stages. If the wedge-storage correction were found to vary with both stage and discharge, a tabulation could be prepared to show the distance to be measured along the M-line from the intersection with the E_2-storage curve for any given combination of stage and discharge. It is to be noted, however, that application of equation (7), from results of investigation of the Lower Cumberland River, appears to offer possibilities for practical use to obtain approximate routings.

Data required for application of equation (7) for routing through the Dover-Smithland reach of the Cumberland River are readily obtained from the curves on Figure 10. The coefficient (1/K), shown on Figure 11, plotted against discharge for parametric values of stage at Smithland, was obtained by measuring the slope of the storage-curves. The values of $P(E_2-E_1)$ required, in addition to the corresponding values of (1/K), to compute the curves shown on Figure 12 were obtained by measurement of the horizontal distance intercepted at given discharge-values between successive pairs of curves for parametric stages at Smithland. On both Figure 11 and Figure 12 a set of radiating lines has been added to provide simple graphical computation of the two terms in equation (7).

The results of routing for the flood of February to March, 1939, on the Cumberland River are shown on Figure 13 for both the graphic procedure and the procedure satisfying equation (7). The computational procedure involved in routing by means of equation (7) is shown by the example in Table 2.

Values of K, N, and (N/K)--It has been observed that the ratio (N/K) generally ranges between 0.2 and 0.3 in river-reaches of the length ordinarily used in flood-routing computations and in which stage-discharge relations at the lower end are unaffected by other streams. It is of interest to note that the value of (N/K) obtained for the several river-reaches considered in the studies reported herein ranged from 0.25 to 0.55 within the range of stage for which data were obtained. The range in values of K, N, and (N/K) for individual reaches is shown in Table 3.

Acknowledgments--The writers wish to acknowledge the cooperation of R. G. West, in direct supervision of the work, of R. L. Irwin, in connection with office studies, and of R. E. Freese, in preparation of the drawings. Basic data were supplied by the Upper and Lower Mississippi Valley Division offices and the Louisville and Nashville District offices of the United States Engineer Department and by the United States Geological Survey. The investigations were made under the direction of Colonel E. H. Marks, Division Engineer, Ohio River Division.

Table 3--Range in values of K, N, and (N/K)

(Does not include storage in the other branch of the Golconda-Thebes-Cairo Reach as in the case of coefficients used for routing)

River	Reach	Length of reach, miles	K	N	(N/K)
Cumberland	Smithland to Dover	88	0.7 - 4.4	0.60 - 1.40	0.24 - 0.42
Ohio	Cairo to Golconda	78	0.20 - 0.90	0.08 - 0.34	0.35 - 0.55
Mississippi	Cairo to Thebes	44	0.10 - 0.45	0.04 - 0.10	0.25 - 0.42

References

[1] E. J. Rutter, Q. B. Graves, and F. F. Snyder, Flood routing, Trans. Amer. Soc. Civ. Eng., v. 104, pp. 275-313, 1939.

[2] G. T. McCarthy, The unit hydrograph and flood routing, paper presented at conference of North Atlantic Division, Corps of Engineers, U.S. Army, June 24, 1938.

[3] I. H. Steinberg, A method of flood routing, Civ. Eng., v. 8, pp. 476-477, 1938.

U. S. Division Engineer Office,
Cincinnati, Ohio

A CONSIDERATION OF FACTORS INFLUENCING RESERVOIR-SEDIMENTATION IN THE OHIO VALLEY REGION

G. M. Brune and R. E. Allen
(Presented by title)

Introduction--In the States of Indiana, Kentucky, Michigan, Ohio, and Tennessee, there are some 440 reservoirs exclusive of farm ponds, built for water-supply, power, flood-control, recreation, or conservation. Their aggregate cost is estimated at $415,000,000.

Approximately 25 of these reservoirs have been studied for the purpose of estimating their rates of silting. Most of the field-examinations were of the nature of a reconnaissance, although data on several reservoirs obtained from published reports were apparently derived from instrumentally controlled surveys. Examinations by the Soil Conservation Service consist of soundings and determinations of depths of sediment at numerous points in the reservoir, but because instrumental control was not used the results, which are averages of the measurements, must be considered only as approximate and not comparable with Soil Conservation Service detailed surveys. They are, however, a useful and inexpensive method of making rough estimates of silting damage and determining the range of magnitude of sediment-production per unit of area. They are probably at least as good as, if not better than, suspended-load records of only one or two years' duration.

The reservoir sedimentation-data thus far obtained in the Ohio Valley Region indicate that the annual rate of depletion of storage-capacity may range from as little as 0.01 per cent, in the case of some of the Muskingum Conservancy District flood-control reservoirs, to as much as 18 per cent, in the case of some ponds built by the Ohio State Division of Conservation.

The fact that there is so great a variation in rates of reservoir-sedimentation in this one region led to the study discussed in this paper, which is an attempt to evaluate, at least roughly, some of the factors influencing these rates.

Factors influencing reservoir-sedimentation--The principal factors influencing rate of silting of reservoirs are: (1) The rate of sediment-delivery to the reservoir; (2) the effectiveness of the reservoir as a sediment trap; and (3) the ratio of reservoir-capacity to amount of sediment-accumulation.

The rate of sediment-delivery to the reservoir depends upon many things. The degree of erosion and relative extent and distribution of the various kinds of erosion, such as sheet, gully, highway, and stream-bank erosion, are important. Soil-type is a factor, especially in regard to the size-particles produced by erosion. Amount of runoff and character of discharge also affect erosion and sediment-transportation. Topographic form, especially the relation of flood-plains and other flat areas to slopes, is important in determining what portion of the eroded material will be deposited as colluvium and alluvium, and therefore will not reach the reservoir [see 4 of "References" at end of paper].

In regard to the effectiveness of the reservoir as a sediment-trap, the most important factor in a given climatic region is the ratio of capacity to drainage-area. Other factors being equal, a reservoir with a large ratio of capacity to drainage-area will offer a greater opportunity for suspended material to settle out than one with a smaller ratio through which the water passes more rapidly [3]. The range of particle-sizes of the sediment delivered is also important in determining what portion will be caught and what portion will pass through or over the dam. The shape of the reservoir will influence the rate of silting. The manner of sedimentation, such as the formation of density-currents and flocculation of the sediment-load, is another factor [6].

Finally there is the purpose of the reservoir and the method of operation of the dam. "Dry" flood-control reservoirs, for example, like those in the Muskingum Conservancy District, usually have sluice-gates at the stream-bed, which are closed only during flood-periods. At all other times water is allowed to flow through these gates, sluicing out a considerable part of the sediment deposited during flood-storage. Much of the sediment is exposed to drying and compaction when the gates are open, and does not regain its former volume when resubmerged. It therefore removes less storage-space than the same weight of sediment continuously submerged.

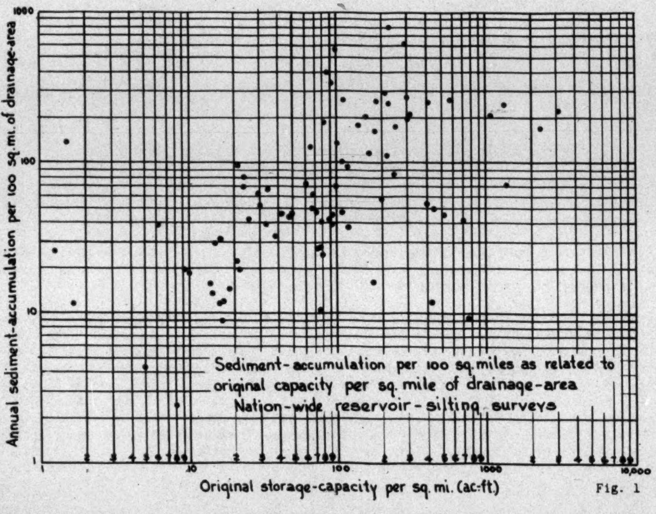


Fig. 1

Method of study--Since there are so many factors involved in reservoir-silting, a quantitative evaluation of all of them, on the basis of existing data, would be impossible. In this study, only two of the most important factors, namely, rate of erosion (sheet- and gully-erosion and ratio of capacity to drainage-area, were considered, and an attempt is made to show in a graphic presentation how these two factors affect reservoir-silting. A third factor, namely, method of operation of the dam, was also considered, inasmuch as all of the reservoirs studied were of the same general type--"permanent-storage" reservoirs.

Figure 1 presents the results of reservoir-sedimentation surveys in various parts of the country, most of them detailed surveys by the Sedimentation Division of the Soil Conservation Service. In this Figure, the relationship of only one factor--ratio of capacity to drainage-area--to sediment-accumulation, is shown. It is evident that when no other factors are considered, the effect of the ratio of capacity to drainage-area on rate of silting in any particular reservoir may vary within wide limits.

For the study under discussion, 23 reservoirs were selected, on whose drainage-areas conservation-surveys, which include measurements of the amount of accelerated, or man-induced, soil-erosion have been made. Eleven of these are in the Ohio Valley Region and 12 in other parts of the country. On Wills Point Reservoir [6], Ardmore Club Lake [6], Grand Saline Reservoir [6], Franklinton Reservoir [6], Lloyd Shoals Reservoir [10], Lake Michie [9], Spartanburg Reservoir [2], University Lake [1], Lake Crook [12], White Rock Reservoir [8], Lake Gibbons [12], and Greensboro Reservoir [6] detailed sedimentation-surveys were made by the Sedimentation Division of the Soil Conservation Service. On O'Shaughnessy Reservoir a detailed survey was made by the Ohio State University. Reconnaissance sediment-measurements were made on the other ten reservoirs.

Since variations in the amount and character of annual rainfall will cause variations in the amount of sediment-production, it was necessary to choose reservoirs that were old enough to provide a reasonably accurate average annual rate of sediment-accumulation. All the reservoirs used in this study were more than ten years old at the time of survey, except O'Shaughnessy Reservoir, Lake Michie, Spartanburg Reservoir, and University Lake. Two--Buckeye Lake and Grand Lake--were old enough (107 and 97 years, respectively) to antedate the beginning of significant man-induced erosion in their drainage-areas.

In determining the amount of accelerated erosion in each drainage-area, "conservation-survey," and other maps made by the Soil Conservation Service, showing degree of erosion, were used. Detailed conservation-survey maps that show the soil-type, slope, land-use, and degree of erosion were available for all the drainage-areas except for 11 reservoirs where reconnaissance-maps were used. Morse's reconnaissance-map of the Muskingum Drainage-Area [11] was used for the drainage-areas of Robbins Lake, Buckeye Lake, and Pond No. 52. The 1934 reconnaissance erosion-maps of Ohio, Indiana, and Illinois were used for the large drainage-areas of O'Shaughnessy Reservoir, Grand Lake, Shafer Lake, and Vermilion Lake.

While the conservation-survey maps afford the only information available at the present time on the degree of accelerated erosion, they do not yield reliable figures for rates of sediment-production. Some of their limitations are as follows [4]: The predominant erosion and not the average erosion in each mapped unit is shown; wide-spread but small areas of colluvial accumulation are not delineated; the average depth of "modern" alluvial deposits is not measured; the volume of material produced by "No. 9" erosion-type, completely gullied areas, from stream-bank erosion and from roadside erosion, cannot be determined from the maps and only an allowance in volume can be made from general observations. The volume of stream-bed material in transit also is not shown on the maps.

Comparisons that have been made of sedimentation with erosion show that the sediment-load entering a reservoir may be expected to range from two or more times the average annual erosion (because of bank-erosion and other forms of erosion not mapped or unexplained) to one-fifth or less (because of colluvial and alluvial deposition not mapped). It is therefore evident that there is no constant ratio between gross erosion as mapped in conservation-surveys, which is essentially any loss of soil from its place of origin irrespective of the distance it is moved, and the sediment-load of a stream draining the area.

Recognizing these limitations and the impossibility of making general application of existing conservation-survey data, nevertheless it appears useful to make comparisons of gross erosion as calculated from conservation-surveys with known rates of reservoir-sedimentation, as one approach to estimating rates of silting. This method should be checked against other lines of evidence, such as suspended-load records and curves based on rates of sediment-production taken from reservoir and stream- and valley-surveys, in estimating silting rates in, for example, some proposed reservoir.

The second factor considered, namely, ratio of capacity to drainage-area, is a readily determinable quantity. One other factor was largely eliminated in this study. This is the method of operation of the dam. All of the reservoirs used are permanent-storage reservoirs that maintain the water-level near maximum capacity storage most of the time. Although some of them have sluice-gates, these are in general rarely opened. Water can ordinarily leave these reservoirs only over the spillway or through intake pipes, which are high enough above the bottom so that the water can carry with it only the very fine sediment that has failed to settle.

In calculating the average rate of accelerated erosion, it was assumed in most cases that the rate of erosion dates from the year when half as much upland was cleared as was cleared when deforestation reached its maximum. It was possible to arrive at this date by projecting backward available census data on the amount of land cleared. For certain reservoir drainage-areas located in the Southeast, where it is known that there have been at least two periods of more active erosion, other methods were used to determine the period. For Buckeye Lake and Grand Lake no assumption as to the period of erosion was necessary, since these lakes existed before significant clearing of their drainage-areas began.

The data from the erosion-surveys were converted into gross volumes of material eroded in each of the drainage-areas in question since the period of accelerated erosion began. This was done by applying the percentage of the surface-soil moved by erosion in each mapped unit to the average depth of that soil-type under virgin conditions, as described in most of the reports on Erosion and related land-use conditions [1, 2, 8, 9, 11]. From these figures, the average annual volumes of material moved from place by erosion were computed. These volumes were compared with the average annual volumes of material caught in the reservoirs.

Assuming that reservoir-sediment in the Ohio Valley Region has a weight of 55 pounds per cubic foot, and that the soil before erosion has a weight of 85 pounds per cubic foot, a correction factor of 64.7 per cent was applied to the volumes of sediment caught in the reservoirs, in order to make them equivalent to the same amounts of soil in place. Actual limits in the region under consideration will run from 80 to 90 pounds per cubic foot for soils and perhaps from 40 to 70 pounds per cubic foot for sediment. In flood-control reservoirs that are dry most of the year, the volume-weight of the sediment may be even higher. Different volume-weights were used for reservoirs in other regions [1, 2, 8, 10].

Discussion of results--The results of these calculations were plotted in Figure 2. Curves may be drawn through these points in several ways, one of which is illustrated by the curve shown. It is also possible to include all of the points within a band which, for the data available, represents the outside limits of the relationship.

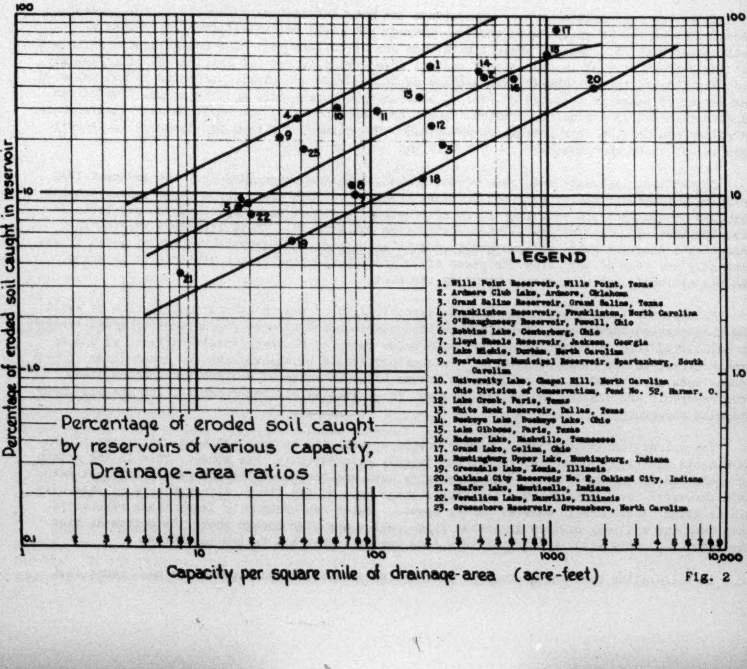


Fig. 2

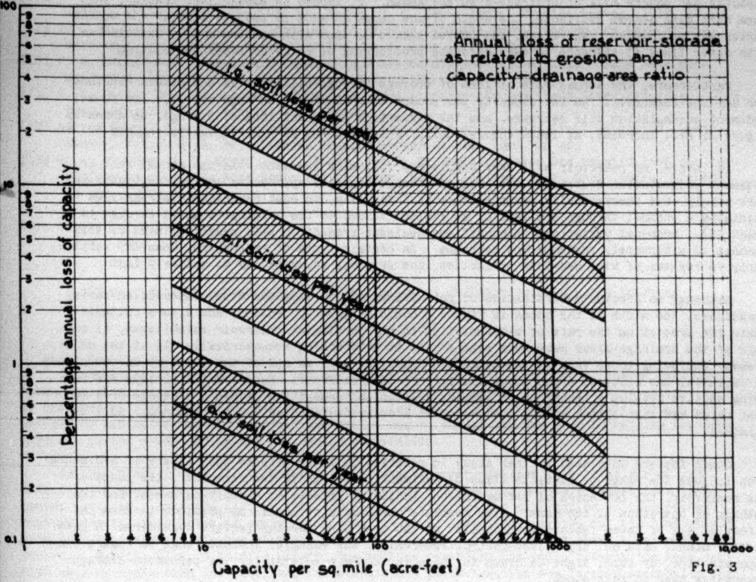


Fig. 3

There is considerable spread among the points because of the many factors that could not be taken into account. There is, however, much less spread than in Figure 1, for although only one factor--ratio of capacity to drainage-area--was considered in Figure 1, three factors, including gross erosion and method of operation of the dam, were considered in Figure 2. The latter factor, however, was only partly considered, since all of the reservoirs studied are of the same general type, namely, permanent-storage reservoirs.

No reservoirs with a capacity of less than eight acre-feet per square mile were used in this study, for the accumulation of sediment in such reservoirs of lower ratio of capacity to drainage-area probably has no relation to erosion on their drainage-areas as measured by conservation-surveys. The sediment in this type of reservoir is very largely bed-load, is related primarily to the factors of stream-velocity, and would probably be transported and fill the reservoir-basins at about the same rate regardless of accelerated erosion.

From Figure 2 it is possible to develop the graph shown in Figure 3. This was done by using the formula $x = (abc/d)$, where x is the percentage of annual loss of storage-capacity, a is soil-loss per year in inches, b is the product (82.62) of a factor for converting square-mile-inches to acre-feet (53.3), and a factor for converting volume of soil to volume of sediment (1.55) assuming that for the Ohio Valley Region the same ratio of volume-weight of soil to volume-weight of sediment may be used for all reservoirs, c is the percentage of eroded soil caught, as shown in Figure 2, and d is the capacity per square mile in acre-feet.

For example, if a is 0.1 inch per year, c is 25 per cent, and d is 150 acre-feet per square mile, $x = (0.1)\ (82.62)\ (25)/150 = 1.3$ per cent annually, as shown in Figure 3.

The data in Figure 3 were developed as bands, just as in Figure 2, in order to show the probable range caused by factors not evaluated in this study. The median curves correspond to the median curve in Figure 2. These bands give an indication of the range of magnitude of silting to be expected for permanent-storage reservoirs when the gross erosion per year and the capacity per square mile of drainage-area are known. It should be emphasized, however, that when more data become available, the width of the bands as well as the position of the median curves may be changed. Therefore, the curves should be used with caution and in association with other lines of evidence to make definite predictions of rates of reservoir-silting.

Furthermore, the annual rate of loss of storage through silting will not remain constant for any one reservoir. As the capacity per square mile decreases through silting, the annual sediment-accumulation will decrease, and the percentage of annual loss of storage, as shown by Figure 3, will increase, at least theoretically, until a point of equilibrium is reached.

In theory, no reservoir will ever completely fill with sediment. As the annual rate of sediment-accumulation decreases, the loss of storage-capacity approaches 100 per cent more and more slowly, but theoretically never reaches it. Actually, in most reservoirs, stream-flow maintains a channel through the lake of equivalent volume to the original channel through this reach [3]. Seasonal variations in runoff and sediment-production will cause the size of this channel to alternately increase and decrease. In certain types of reservoirs, however, particularly in regions of high bed-load production, the original capacity may be entirely lost.

Although no precise determination of soil-losses can be expected from conservation-survey techniques, the width of the bands in Figure 3 could be greatly reduced, and a more reliable basis for predicting the rate of sedimentation in any particular reservoir established, if surveys of the drainage-areas were made with a view to determining volumetrically all of the soil-losses, including those from stream-banks and roads, as well as all of the sediment-accumulations in colluvial and alluvial areas above the site of the reservoir. Experimental surveys are now being made to develop a technique of mapping erosion and deposition within a drainage-area so that total sediment-output during the period of accelerated erosion can be reasonably well determined.

Other factors that need further study in relation to their effects upon reservoir-sedimentation include the range of particle-sizes of sediment delivered to the reservoir, the shape of the reservoir, the processes of sedimentation, including effects of density-currents, and the methods of operation of the dams. With adequate basic data it should be possible to show the effect of all of these factors graphically, as has been done for the factors considered in this study. Scanty data on "dry" flood-control reservoirs, for example, indicate that in Figure 2 a separate line, or band, might be drawn for them in contrast to that for the permanent-storage reservoirs used in this study.

Summary--A study was made of certain factors causing a wide variation in rates of reservoir-silting, especially in the Ohio Valley Region. The factors of gross annual erosion in the drainage-area, capacity of the reservoir per square mile of drainage-area, and, partly, method of operation of the dam, were considered in this study, and the results were plotted graphically. Because of the many factors that could not be evaluated, there was considerable spread in the points as plotted on the graph. This study provided an indication, however, of the range of magnitude of silting to be expected for permanent-storage reservoirs, but the results should be used only in association with other evidence to make definite predictions of rates of silting in particular reservoirs. No exact evaluation of the various controlling factors can be made from existing data. Of the further work necessary in this field, probably the most important single item is the development of special erosion-surveys, so designed as to furnish a much more accurate index of sediment-production than the present conservation-surveys provide.

References

[1] T. C. Bass and I. L. Martin, Erosion and related land use conditions on the University Lake Watershed, Chapel Hill, North Carolina, U. S. Dept. Agric. Erosion-Survey, 1939, 16 pp.

[2] T. C. Bass and I. L. Martin, Erosion and related land use conditions on the Spartanburg Municipal Reservoir Watershed, South Carolina, U. S. Dept. Agric. Erosion-Survey, 1940, 16 pp.

[3] C. B. Brown, Rates of silting in representative reservoirs throughout the United States, Trans. Amer. Geophys. Union, pp. 554-557, 1937.

[4] C. B. Brown, Sedimentation studies by the Soil Conservation Service, 1939-1940, Report of Comm. on Sedimentation, Nation. Res. Council, 1939-1940, December 1940.

[5] G. M. Brune and R. E. Allen, A graph for use in estimating rates of reservoir silting, Soil Conserv. Serv., Region 3, Tech. Notes No. 4, March 1941.

[6] H. M. Eakin, Silting of reservoirs, U. S. Dept. Agric. Tech. Bull. 524, 1936, 142 pp. (revised by Carl B. Brown, August 1939).

[7] A. M. Edwards, Silting of the O'Shaughnessy Reservoir, Civ. Eng., v. 6, pp. 511-512, 1936.

[8] R. M. Marshall and C. B. Brown, Erosion and related land use conditions on the Watershed of White Rock Reservoir, near Dallas, Texas, U. S. Dept. Agric. Erosion-Survey, 1939, 29 pp.
[9] I. L. Martin and T. C. Bass, Erosion and related land use conditions on the Lake Michie Watershed, near Durham, North Carolina, U. S. Dept. Agric. Erosion-Survey, 1940, 19 pp.
[10] P. H. Montgomery, Erosion and related land use conditions on the Lloyd Shoals Reservoir Watershed, Georgia, U. S. Dept. Agric. Erosion-Survey, 1940, 26 pp.
[11] H. H. Morse, Erosion and related land use conditions on the Muskingum River Watershed, U. S. Dept. Agric. Erosion-Survey, 1939, 36 pp.
[12] Harvey Oakes, Erosion and related land use conditions on the Lake Crook Watershed, Lamar County, Texas, U. S. Dept. Agric. Erosion-Survey No. 14, 1940, 23 pp.
[13] W. W. Stevens, H. V. Bragg, E. C. Sease, and O. C. Lewis, Erosion and related land use conditions on the Reedy Fork Demonstration-Area, North Carolina, U. S. Dept. Agric. Erosion-Survey, 1938, 21 pp.

Soil Conservation Service,
Dayton, Ohio

THE HEAT-BALANCE METHOD FOR THE DETERMINATION OF EVAPORATION FROM WATER-SURFACES

Benjamin Holzman

(Presented by title)

Introduction--The first law of thermodynamics requires that a balance of energy exist between the loss and gain in heat at the surface of a body of water. Thus, the insolational energy absorbed at a water-surface may be equated to the heat-losses from the surface through the process of radiation, conduction, and convection and to the energy expended in raising the temperature of the water and in the process of evaporation.

In 1915 Schmidt [see 11 of "References" at end of paper] applied this principle of conservation of energy to the problem of evaporation and computed the moisture-losses from large bodies of water. Ångström [1], in 1920, published a paper on the application of this energy-equilibrium to the problem of evaporation from lakes and adequately pointed out its limitations. Schmidt's treatment of various elements in the heat-balance relations was shown to be unsatisfactory. Specifically, Schmidt's general assumptions regarding the ratio between the heat carried away by convection and heat used for evaporation which involved the further assumption that the water-bodies under consideration will be generally warmer than the air were held untenable.

Cummings and Richardson [5, 8] have also made use of the conservation-of-energy principle in their work on evaporation. Expressed as an equation, their heat-balance parameters are written as

$$I = B + S + K + C + LE \qquad (1)$$

where I = incoming radiation per square centimeter of surface, B = back-radiation to the sky, S = energy expended in changing the temperature of the water, K = a correction due to heat derived from the air or given up to the air as sensible heat, C = corrections such as heat-leakage through the walls of the container, expansion of the water, or in the case of a lake, for heat carried by flowing water, L = heat of vaporization of water, and E = evaporation.

The quantity K is defined as K = LER, where R is presumably the sensible-heat exchange due to turbulent transfer divided by the latent-heat exchange due to the vaporization of water. When K is eliminated, the evaporation-formula becomes

$$E = (I - B - S - C)/L(1 + R) \qquad (2)$$

Cummings [3, 4] has indicated the order of magnitude for the essential components of this equilibrium as follows: I may vary from 0 to 70 or 80 calories/hr/cm^2, B is always positive and may range in value from slightly greater than 0 to about 10 calories/hr/cm^2, S varies from -10 to +10 calories/hr/cm^2, C is generally negligible for a lake but may be as high as 10 calories/hr/cm^2 for a pan, and R for short time-intervals varies from -1 to +1 but is seldom greater than 0.30 and is frequently less than 0.20 for 24-hour intervals.

By considering S and C negligible, R as having the constant value 0.22, and using the value 585 for the latent heat of evaporation, Richardson [9] has simplified equation (1) to the following:

$$E = (I - B)/2.54 \times 585 \times 1.22 = (I - B)/1814 \qquad (3)$$

where E is the evaporation in inches of depth.

Evaluation of the heat-balance parameters

The insolation-term--It is at once apparent that I, the energy received from the Sun, comprises the principal component of this equilibrium. I will depend upon the solar altitude, length of day, cloudiness, haziness, and other factors affecting the absorption, scattering, or reflection of the radiation. By means of recording thermoelectric pyrheliometers I may be measured very accurately, but Weather Bureau stations equipped with measuring devices number less than ten for the United States.

Richardson [9] suggests computing I from a knowledge of the solar constant, altitude of the Sun, latitudinal position of the body of water for which the evaporation is desired, etc.; or, in other words, simply considering the problem as a geometric one. Obviously, because of the uncertainty in the transmission, adsorption, and reflection of the Sun's radiation in the Earth's atmosphere, such a calculated value for I at the most can only be a rough estimate.

Richardson and Montgomery [10] have suggested the evaluation of I by means of heat-balance relationships making use of observations of evaporation from heat-insulated pans. The method is identical to that outlined above for determining the evaporation from reservoirs or lakes, with the exception that I becomes the unknown in the heat-balance equation instead of E. Because of the uncertainty in the determination of the convective-heat component in the heat-balance equation as discussed below, the evaluation of I by this technique is not considered reliable.

The back-radiation term--The term B represents the net exchange-energy due to radiation from the body of water and the atmosphere. Richardson [9] uses the following formula for the determination of B:

$$B = 0.906\gamma\, T_w^{\,4} - b\, T_a^{\,4} \qquad (4)$$

The fraction 0.906 corrects for the fact that water does not radiate as a perfectly black body; γ is the Stefan-Boltzmann radiation-constant amounting to 5.7×10^{-5} erg per cm^2 per sec per degree to the fourth power; b is an empirical constant that presumably permits the use of air-temperature in computing the radiation from the atmosphere.

There is no theoretical basis for the constancy of b. Based upon observations from four stations--Fort Collins, Colorado, San Francisco, California, Pasadena, California, and San Diego, California--Richardson [9, p. 1004] determined its average value to be 0.790. This value may be considerably in error because of the limited observational data. More fundamentally, the criticism for the use of b is to be directed at its complete empiricism. The radiation from the atmosphere is a complex function of the moisture- and temperature-distribution, cloudiness, haziness, and other factors. Recently Elsasser [6] has suggested a technique for the graphical computation of the radiation from the atmosphere for which upper-air soundings of temperature, humidity, and pressure are required. Aerological soundings are becoming more numerous and in the future it is to be expected that the radiation from the atmosphere can be evaluated with great accuracy.

Energy-changes within the water-body--The quantity S represents the radiational energy expended in warming or cooling of the water. During the day, the temperature of the water increases because a considerable portion of the insolational energy may be absorbed. At night, the outgoing radiation generally exceeds the incoming radiation from the atmosphere; consequently, the water-temperature decreases. The heat-content of the water-body will also be affected by the temperature of water that flows into the lake and by temperature-changes due to conduction of heat through the bottom and sides of the lake; these incidental energy-changes are represented by C. The quantity C is usually very small for a lake. These energy-changes within the water-body can be readily determined with sufficient accuracy by making use of water-temperature soundings.

The heat-changes due to conduction and turbulent transfer--In the atmosphere heat may be transferred by three different processes--conduction, radiation, and convection. Conduction is the least important of the three. Air is a very poor conducting medium and consequently the simple molecular dispersal of heat through air takes place extremely slowly. Radiation is a very important process in heating and cooling of the atmosphere and is fundamental in maintaining an energy-balance. Convection which may be considered as a turbulence-process is of utmost importance in changing the energy-structure of all the air-masses that move about on the Earth.

In considering the energy-exchanges that occur between the atmosphere and a boundary-surface such as of a lake, it is important to recognize that there are two types of air-flow whose characteristics are distinct and different and govern the speed with which the transport of heat or other physical properties may take place. The laminar current is directly in contact with the lake. The thickness of the laminar layer is extremely variable and largely depends upon the wind-velocity and the roughness-character of the surface. Heat- and moisture-dispersal through this layer can only occur by molecular conduction or diffusion. Above the laminar layer lies the layer of turbulent flow. This layer is quite thick, frequently exceeding several hundred meters. Here the transport of heat or moisture is carried on by means of eddy or turbulent motion which operates so rapidly compared to molecular motion that the latter action, as indicated before, is relatively inconsequential in bringing about changes in the physical properties of air-masses.

The quantity K in the heat-balance equation represents the exchange of heat between the atmosphere and the lake. This heat may be abstracted from the atmosphere, being transferred from the turbulent layer to the laminar layer and then to the lake-surface, or it may be given up to the air by conduction through the laminar layer and then rapidly dispersed throughout the turbulent layer. The latent heat stored in the transport of water-vapor is not included in the K-term. It might appear that the laminar layer, being adjacent to the evaporating surface exerts a controlling influence on the rate at which heat may be transferred. This would be true only in absolutely calm conditions which rarely if ever obtain in the atmosphere. The thickness of the laminar layer is completely controlled by the conditions in the turbulent layer. When turbulence is at a maximum, the thickness of the laminar layer is at a minimum, and thus a rapid transmission of heat occurs for a given difference in temperature between the lake and air. For the same difference in temperature only a very slow transmission of heat occurs when the laminar layer is thick, at which time turbulence in the layer above necessarily is greatly suppressed.

Since the same physical laws are operative in either the exchange of heat or moisture between the lake and atmosphere, Bowen [2], on the basis of similarity, developed an equation which expresses the ratio of the sensible-heat exchange to that latently stored by evaporation or condensation in the transfer of water-vapor. This ratio is designated as R. The quantity, K, in the heat-balance equation may then be evaluated by letting K = LER.

The equation for R is

$$R = 0.46\ [(T_w - T_a)/(P_w - P_a)](P/760) \qquad (5)$$

Where T_a and P_a are the original temperature and vapor-pressure of the air passing over the lake or body of water expressed in degrees Centigrade and mm of mercury, T_w and P_w are the corresponding quantities for the layer of air in immediate contact with the water-surface. P is the barometric pressure in mm.

It is to be pointed out that when R = -1, a steady-state condition is implied and the formula for the Bowen ratio reduces to the psychrometric equation. The energy lost by evaporation is then exactly balanced by a gain of energy to the evaporating surface. This equilibrium is reached only after a critical turbulence is obtained. It is well known that a critical velocity of ventilation is required for obtaining reliable wet-bulb temperatures, which is merely another way of saying that a critical turbulence is needed to transfer moisture away from the wet bulb and to conduct heat to the wet bulb. Should there be improper or insufficient ventilation of the psychrometric tube the critical turbulence-value will not be reached, and thus the energy-balance will no longer be maintained. In other words, R is no longer equal to -1, but becomes a variable quantity depending upon the characteristic turbulence-condition above the evaporating surface.

When the temperature of the air is less than the temperature of the lake-surface, the vapor-pressure in direct equilibrium with the water-surface is always greater than the vapor-pressure of the air. This means that R is a positive quantity. On the other hand, when the temperature of the air exceeds that of the water, the vapor-pressure of the air may be either greater or less than that corresponding to the temperature of the lake-surface. If P_a is greater than P_w, R is a positive quantity. If P_a is less than P_w, R is a negative quantity. Thus, it is apparent that R may vary considerably and will depend very largely upon the prevailing meteorologic conditions. It is not expected that R should remain fairly constant even when averaged for periods of a month or longer, such as Richardson has assumed, because the ratio is a function of temperature-, humidity-, and turbulence-conditions which for any one period may depart considerably from average conditions.

In his derivation of the equation for R, Bowen assumed laminar flow throughout. The coefficients of vapor-diffusion and heat-conduction were employed in setting up the heat-transfer equations. Consequently, the observations of P_a and T_a are restricted to the laminar layer. Since the laminar boundary-layer has a variable thickness, frequently of the order of one mm or less, it is impracticable to make the necessary observations in order to determine R. When measurements of P_a and T_a are made they are almost invariably representative of the turbulent atmosphere and when substituted in Bowen's equation a value for R will be obtained that will have no theoretical validity.

In recent years, however, increased knowledge regarding the turbulence-transport coefficient (Austausch) has enabled various workers [7, 12, 13] to determine the vertical vapor-transport from a body of water by means of humidity and wind-gradient measurements in the turbulent atmosphere.

The equation for evaporation based upon these parameters is

$$E = \rho k_0^2 (q_1 - q_2)(w_2 - w_1)/[\log_e (z_2/z_1)]^2 \tag{6}$$

where ρ is the density of the air, k_0 is universal turbulence-constant, q_2 and q_1 are the specific humidities of the air at level z_2 and z_1, respectively, above the evaporating surface, and w_2 and w_1 are the wind-velocities at the corresponding levels z_2 and z_1.

A similar equation for the transfer of heat can be written

$$H = \rho^2 c_p k_0 \ (t_1 - t_2)(w_2 - w_1)/[\log_e (z_2/z_1)]^2 \tag{7}$$

where c_p is the specific heat at constant pressure and t_2 and t_1 are the temperatures of the air at level z_2 and z_1, respectively, above the evaporating surface.

Thus a ratio of the sensible-heat exchange due to turbulent transfer to that of the latent-heat exchange due to the vaporization of water can be easily obtained by dividing H by E. This ratio would have some similarity to the Bowen equation in that the ratio will be proportional to a temperature-difference and inversely proportional to a vapor-pressure difference. But these two ratios are quite dissimilar, one being based upon transfer by conduction and the other by turbulent transfer.

Cummings has recognized the trouble involved in determining the convective component, K, in the heat-balance equation, but has assumed that the Bowen ratio conveniently eliminates the difficulty in determining this quantity. It would seem that until a more rigorous method for determining the heat-exchanges due to convection is applied, the evaporation from a body of water as computed from the heat-balance equation may be considerably in error. With respect to this point, Richardson [9, p. 1008], using the heat-balance method, computed the evaporation from Chesapeake Bay to be 124.3 cm per year, and favorably compared this to a value 120.0 cm, which was later pointed out to be the precipitation value.

Conclusion--The heat-balance method for determining evaporation from water-bodies is known to be theoretically precise. However, the difficulties to be encountered in accurately measuring most of the essential parameters in the heat-balance equation appear to invalidate the practical usefulness of this technique.

A direct determination of evaporation by using measurements of humidity and wind-gradient in the turbulent atmosphere is suggested.

References

[1] Anders Ångström, Applications of heat radiation measurements to the problems of the evaporation from lakes and the heat convection at their surfaces, Geogr. Ann., v. 2, pp. 237-252, 1920.

[2] I. S. Bowen, The ratio of the heat losses by conduction and by evaporation from any water surface, Phys. Rev., v. 27, pp. 779-787, 1926.

[3] N. W. Cummings, Evaporation from water surfaces: Status of present knowledge and need for further investigations, Trans. Amer. Geophys. Union, Part II, pp. 507-509, 1936.

[4] N. W. Cummings, The evaporation-energy equations and their practical application, Trans. Amer. Geophys. Union, pp. 512-522, 1940.

[5] N. W. Cummings and Burt Richardson, Evaporation from lakes, Phys. Rev., v. 30, pp. 527-534, 1927.

[6] W. M. Elsasser, An atmospheric radiation chart and its use, Quart. J. R. Met. Soc., v. 66, pp. 41-56, 1940.

[7] R. B. Montgomery, Observations of vertical humidity distribution above the ocean surface and their relation to evaporation, Papers Phys. Oceanogr. Met., Mass. Inst. Tech. and Woods Hole Oceanogr. Inst., v. 7, p. 33, 1940.

[8] National Resources Planning Board, Deficiencies in hydrologic research, 1940.

[9] Burt Richardson, Evaporation as a function of insolation, Trans. Amer. Soc. Civ. Eng., v. 95, pp. 996-1011, discussion pp. 1012-1019, 1931.

[10] Burt Richardson and Carol Montgomery, The measurement of insolation by means of a pan, Natl. Res. Council Bull. 68, pp. 56-61, 1929.

[11] W. Schmidt, Strahlung und Verdunstung an Freien Vasserflachen, Ann. Hydro. Marit. Met., v. 3, p. 4, 1915.

[12] H. U. Sverdrup, On the evaporation from the oceans, J. Mar. Res., v. 1, pp. 3-14, 1937.

[13] C. W. Thornthwaite and Benjamin Holzman, The determination of evaporation from land and water surfaces, Mon. Weath. Rev., v. 67, pp. 4-11, 1939.

U. S. Weather Bureau,
New York, New York

DISCUSSION

HERBERT C. S. THOM (U. S. Weather Bureau, Washington, D. C.; communicated)--The writer is in general agreement with the author as to the futility of attempting to measure evaporation by the heat-balance method due to the multiplicity of difficulties involved in measuring the various factors. The most natural way of measuring the flow of any material is actually to measure that flow volumetrically. This is the essence of the turbulent-transport method being developed by the Weather Bureau for measuring evaporation from open water-surfaces.

With reference to the author's discussion of insolation, it is doubtful whether upper-air soundings on any possible scale would make Elsasser's technique useful in computing radiation received by a lake or reservoir. Radiation is greatly affected by local cloudiness which obviously cannot be determined by soundings. Furthermore, the accuracy of humidity-observations of radiosondes are now questionable and there is little possibility of their ever being adequate for this purpose. It is difficult to see from the author's explanation how the turbulent layer can affect evaporation since, as he states, the laminar layer is in contact with the water-surface and therefore must govern the flow of water-vapor to the atmosphere. Evaporated moisture, according to this explanation, would first have to be transported by molecular diffusion and little evaporation therefore could result. The logical explanation involves the concept of a semi-laminar boundary-layer as postulated by Brunt [see p. 282 of 1 of "References" at end of discussion]: "The 'boundary-layer' is a time-mean phenomenon, and it is not to be supposed that this layer is always constituted of the same fluid. The turbulence which may prevail at some distance from the boundary will from time to time break through the layer, carrying away portions of the fluid which instantaneously constitute it, but as soon as the individual eddy has removed a portion of the boundary-layer normal processes will tend to build it up again."

It is noteworthy that the writer, unfamiliar with Bowen's equation, computed and made use of a similar equation in connection with data furnished certain consulting engineers for their design of sewage-disposal equipment. The problem was to determine the relative effect of evaporation in cooling open-water surfaces in treatment tanks. By dividing Sverdrup's equations for heat- and moisture-flow [the author's equations (6) and (7)], the writer obtained the ratio

$$R = (H/E) = 0.66\,(T_b - T_0)/(e_0 - e_b)$$

in which T_b is the air-temperature and T_0 the water-temperature °absolute scale, e_b is the vapor-pressure of the air, and e_0 is the vapor-pressure of the water in millibars. In this problem T_b was greater than T_0 and the effects of the convection of water-vapor and heat tend to be compensatory.

There is some question of the author's postulation of a critical turbulence being compatible with fact, since the convection of heat is dependent only on air-temperature whereas vapor-pressure is dependent on specific humidity as well as temperature. The factor that is critical therefore is the specific humidity and not the turbulence. It has been shown conclusively by Arnold [2] that there is no such thing as a critical ventilation-velocity and that evaporation from a wet-bulb thermometer continues to increase as the ventilation-velocity tends to infinity. The convection of heat to the wet-bulb thermometer is relatively unimportant compared to the radiation from the air to the wet bulb. The fact that R = -1 therefore has little meaning in relation to the wet-bulb thermometer.

[1] David Brunt, Physical and dynamical meteorology, 1st ed., 1934.
[2] J. Howard Arnold, The theory of the psychrometer, Physics, v. 4, pp. 255 et seq, 1933.

INTERCEPTION OF RAINFALL BY MATURE LODGEPOLE-PINE

H. G. Wilm and C. H. Niederhof
(Presented by title)

Introduction--With increasing demands on available water-supplies for agricultural, industrial, and domestic use, the central Rocky Mountains have become one of the most important water-yielding areas in the western United States. Since the water-producing area of these mountains is largely occupied by national forests, a serious responsibility is borne by the Forest Service in providing proper land-management for the yield of usable water. As proper management requires a detailed knowledge of the influence of forests on water-yields, the Forest Service has started an intensive program of watershed research in the Rocky Mountain region.

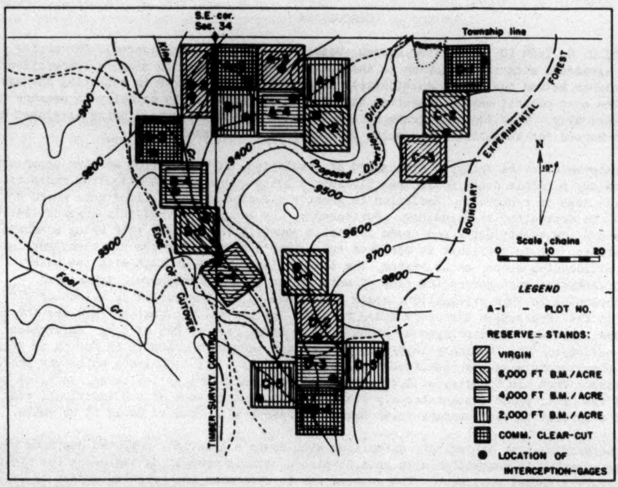

S.E. cor.
Sec. 34
Township line
King
Cr.
Proposed
Proposed Diversion Ditch
EXPERIMENTAL FOREST
BOUNDARY
9100
9200
9300
9400
9500
9600
9700
9800
Edge of Cutover
Timber-Survey Control
Fool Cr.
A-1
A-2
C-2
C-3
C-5
C-6
D-1
D-2
D-3
N
13°
Scale, chains
0
10
20
LEGEND
A-1 - PLOT NO.
RESERVE - STANDS:
▨ VIRGIN
▧ 6,000 FT B.M./ACRE
▤ 4,000 FT B.M./ACRE
▥ 2,000 FT B.M./ACRE
▦ COMM. CLEAR-CUT
● LOCATION OF INTERCEPTION-GAGES

Fig. 1--Map of experimental area, showing plot- and block-arrangement, treatment applied to each plot, and location of interception-gages

Among these investigations, a study has been designed to determine the influence of lodgepole-pine stands upon the interception of summer rainfall by tree-crowns. After evaluation of the quantity of these losses in virgin forests, a second objective of the study is to determine the extent to which interception may be reduced by partial removal of commercial timber-stands.

These experiments were started in 1938 on the Fraser Experimental Forest, in the headwaters of the Colorado River near Fraser, Colorado. After three years of records, pertinent results of considerable value and interest have been obtained.

Experimental design--All measurements were taken in a group of 20 silvicultural plots, each five acres in area, established for study of the influences of timber-cutting on tree-growth as well as on water relationships. These plots were grouped in four blocks of five plots (Fig. 1), so that four cutting treatments could be compared with a virgin plot in each block.

Table 1--Gross and net rainfall in a mature lodgepole-pine forest

Plot-treatments[1]	None	Light	Medium	Heavy	Clear
(A) Before treatment					
Average merchantable volume					
Board feet per acre	11,890	12,770	12,200	10,710	12,740
1938 (based on 32 storms)					
Gross rainfall, inches	7.10	6.90	7.33	7.08	7.16
Net rainfall, inches	4.86	5.14	4.95	5.03	5.17
Net rainfall, per cent of gross	68.45	74.49	67.53	71.04	72.21
1939 (based on 15 storms)					
Gross rainfall, inches	3.64	3.50	3.86	3.62	3.75
Net rainfall, inches	2.38	2.44	2.64	2.59	2.74
Net rainfall, per cent of gross	65.38	69.71	68.39	71.55	73.07
1938-1939 combined (47 storms)					
Net rainfall, per cent of gross	67.41	72.88	67.83	71.21	72.50
(B) After treatment					
Average merchantable volume					
Board feet per acre	11,890	6,000	4,000	2,000	0
1940 (based on 43 storms)					
Gross rainfall, inches	11.00	10.92	11.31	10.96	11.18
Net rainfall, inches	7.86	9.67	10.67	9.78	10.23
Net rainfall, per cent of gross	71.45	88.55	94.34	89.23	91.50

[1] Columns indicate relative intensity of cutting applied to each group of plots, as shown quantitatively under "merchantable volume, after treatment."

One hundred rain-gages were distributed over the experimental area, with a group of five on each of the 20 plots. For measurement of "gross" rainfall, one of the gages in each group was placed in an opening at least 25 feet in diameter, selected at random from all available openings on a plot. The other four gages were placed 66 feet (one chain) from the "open" gage--one in each of the four cardinal directions. This group of four gages was assumed to sample adequately the "net" rainfall which reaches the ground under tree-crowns.

Records of gross and net rainfall were collected after each storm during the three seasons of study. For the first two seasons all 20 of the plots were in a virgin condition; during the winter between the second and third seasons the plots were cut-over experimentally. A random selection was made to determine which treatment each of the five plots in a given block was to receive; then four of the plots within each block were cut-over, leaving the following reserve stands of commercial timber: Zero (all trees over 10 inches in diameter removed); 2,000 board-feet; 4,000 board-feet; and 6,000 board-feet. As a check, one plot in each block was left in the virgin condition.

Since some intercepted rainfall may return to the soil by flowing down the trunks of trees, the amount and variability of stemflow due to differences in tree species, crown-condition, diameter, and cutting methods were determined as a secondary phase of the investigations. One hundred and eight trees were selected; 54 in a reserve stand of 6,000 board-feet per acre and 54 in an adjacent virgin stand. Within each of these two stands stemflow was measured for lodgepole-pine (Pinus contorta), Englemann spruce (Picea Engelmannii), and alpine fir (Abies lasiocarpa), the three important tree-species found in virgin stands on the experimental forest. Six diameters, ranging in two-inch classes from four to 14 inches, were considered for each species. Within each diameter class, three crown-classes were considered. Class "A" crowns included trees with vigorous, wide, well-developed crowns; class "B" was confined to trees with less vigorous, narrower, and shorter crowns than class "A"; and trees with very poor vigor and very short, narrow, thin crowns were grouped in class "C".

The apparatus used to measure stemflow consisted of a lead trough fastened tightly around each tree, with a copper spout and rubber hose conducting stemflow from the tree to a collector-

Table 2--Variance and covariance of net rainfall and gross rainfall

(Before treatment, 1938-39)

Source of variation	Errors of estimate	
	Degrees of freedom	Mean[1] squares
Total	938	0.0011
Between: "Treatments"	4	0.0097
Blocks	3	0.0099
Interaction (error)	11	0.0304
Remainder	919	0.0007

Regression-statistics for "remainder": $E = 0.8114X - 0.0247$; $r = 0.990$.

[1] Squared standard deviations; none of the variances differed significantly from "error."

can. The amount of stemflow in each can was measured in cubic inches after each storm. Measurements of stemflow were made only during the last season of the interception-study, so that a comparison could be made between cut-over and virgin stands.

Results of the study

Interception--During the first two years (1938 and 1939) both gross and net rainfall were fairly uniform among the plot-groups selected for different intensities of cutting (Table 1). This fact, together with the similarity of merchantable timber-volume found on all the plot-groups before treatment, indicates the relative homogeneity of the stand and the character of rainfall. Differences in gross rainfall due to variations in elevation and exposure are apparently ironed out by randomization of proposed treatments throughout experimental area. Net rainfall in per cent of gross rainfall was found to be almost the same in both 1938 and 1939, indicating that relative amounts of intercepted rainfall do not vary to any appreciable extent between years.

By combining the data for 1938 and 1939 and comparing them with figures of 1940 (after treatment) it was found that the percentage of net rainfall increased considerably, and therefore interception was diminished, on all the treated plots. The plots which were left in a virgin condition in 1940 showed approximately the same relative net rainfall as in previous years, indicating that increases on the treated plots were due to the effects of treatment and not to an abnormal year.

A striking feature of Table 1 is the high net rainfall measured on the group of plots with a 4,000-foot reserve stand; actually higher than that found on the "clear-cut" plots. Apparently the discrepancy is purely the result of cutting, as this group of plots showed reasonable agreement with the other plots before treatment. In this one group of plots, cutting must have been unusually heavy around the rain-gages on each plot, so as to give the effect of commercial clear-cutting rather than of a 4,000-foot reserve stand.

In order to determine the influence of storm-size as well as of treatment and block effects on net rainfall per storm, the data were analyzed by covariance [George W. Snedecor, Statistical methods, third ed., Iowa State College Press, 1940]. Records for 1938 and 1939 were combined for the phase of the study before treatment (Table 2), and the 1940 data were analyzed separately (Table 3). In these analyses, as in any randomized-block experiment, the block-treatment interaction formed the appropriate measure of "error" for testing the effects of treatment. The significance of regressions of net rainfall on gross rainfall was tested by the regression-errors of estimate.

As shown in Table 2, no significance variance was found before treatment between blocks, nor between the plots selected for treatment. This fact bears out the conclusion, drawn from inspection of average figures in Table 1, that the study area was relatively homogeneous as regards interception of rainfall by the virgin forest.

A corresponding analysis of covariance of the 1940 data shows that the cutting treatments had a strong effect ($F = 13.70$) in augmenting net rainfall. As pointed out by further study of average net rainfall (Table 1), all of the treatments appear to have exerted approximately the same influence; net rainfall, in other words, failed to vary in proportion to intensity of treatment.

The regression-statistics for "remainder" in each covariance analysis present another interesting feature of the study (Tables 2 and 3; Fig. 2). (In the regression-formulas, E is estimated net rainfall, and X is any value of gross rainfall.). In 1938 and 1939, for example, the storage-capacity of trees in a virgin stand was approximately 0.025 inch of rain. After this storage was filled in any given storm, net rainfall should logically be equal to the remaining gross rainfall, minus stemflow and evaporation from tree-crowns during the storm. As will be shown later, stemflow is negligible in volume; hence, any deviation of the regression-line from a unit-relation between net and gross rainfall should express the amount of evaporation from tree-crowns during

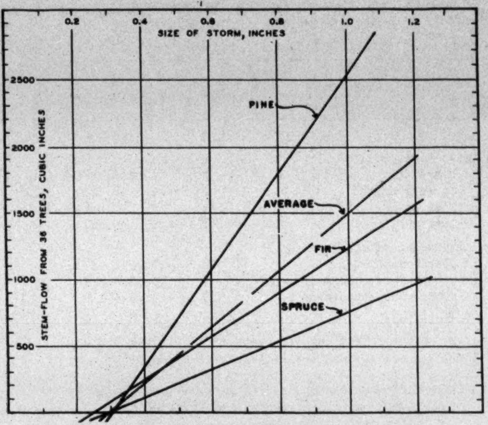


Fig. 2--Influence of timber cutting on relation of net rainfall to size of storm (gross rainfall)

Table 3--Influence of cutting treatment on net rainfall under lodgepole pine, adjusted for variations in gross rainfall, 1940

Source of variation	Degrees of freedom	Mean squares
Total	858	0.0021
Between: "Treatments"	4	0.0836[a]
Blocks	3	0.0199
Interaction (error)	11	0.0061
Remainder	839	0.0015

[a] Highly significant ($p < 0.01$).

Regression-statistics for individual treatments, with block variance removed: Virgin, $E = 0.8151X - 0.0258$, $r = 0.978$; 6,000, $E = 0.9321X - 0.0118$, $r = 0.984$; 4,000, $E = 0.9651X - 0.0056$, $r = 0.990$; 2,000, $E = 0.9048X - 0.0032$, $r = 0.965$; 0, $E = 0.9478X - 0.0083$, $r = 0.993$. The individual regressions differ significantly from the average regression of all treatments ($F = 19.13$).

storms. Since the regression-coefficient for the period of 1938-39 is 0.8114, apparently about 19 per cent of each storm was lost by evaporation during the storm-period, in addition to initial losses by crown-storage. Although this loss seems surprisingly large, it may be explained by the character of summer storms in this region, occurring in intermittent showers and often falling in relatively unsaturated atmosphere. For the trees studied, this relation seems to be very accurate, as shown by an extremely high coefficient of correlation (0.990).

In 1940, the uncut plots showed an almost identical regression (Table 3 and Fig. 2), supporting the results of earlier years. By contrast, all of the treated plots produced regressions with decidedly steeper slopes. The initial storage-capacity of crowns was lowered on the cut-over areas (0.003 to 0.012 inch of rain), and the slopes of regression-lines tended to approach unity (0.905 to 0.965).

Table 4--Statistics of variation for stemflow in the lodgepole-pine type, in cubic inches

(A) Variance of stemflow

Source of variation	Degrees of freedom	Mean squares
Total	107	19,235.50
Between means of		
Diameters	5	7,808.00
Crown classes	2	18,136.73
Species	2	79,092.00[b]
Treatments	1	11,165.03
Significant interactions		
Diameter-crown class	10	30,238.47[a]
Diameter-treatment	5	39,533.65[a]
Crown class-treatment	2	36,614.72[a]
Multiple interaction (error)	20	11,810.65

All interactions were computed--only the significant interactions are shown

(B) Regression-statistics for total stemflow in cubic inches per storm, by species, on total rainfall in inches per storm

Lodgepole pine, $E = 3583.0X - 1090.1$, $r = 0.881$
Alpine fir, $E = 1603.1X - 386.6$, $r = 0.844$
Engelmann spruce, $E = 1034.6X - 300.9$, $r = 0.917$

All correlations are highly significant ($p < 0.01$)

---

[a] Significant ($p < 0.05$). [b] Highly significant ($p < 0.01$).

Stemflow--In this study stemflow was found to be low in quantity; of the 43 storms which produced 11.3 inches of rainfall during the summer of 1940, only nine storms produced stemflow. Assuming an average crown-diameter of ten feet, the stemflow per tree totaled less than 0.01 inch of rainfall for the entire season.

Even though this quantity is quite negligible, variance and covariance analysis of the stemflow-data produced results of some academic interest (Table 4). Of all factors studied, only the three species showed a strong influence; spruce yielded the least stemflow, fir an intermediate amount, and pine the greatest volume.

Apparently the method of crown-description used in this investigation did not adequately classify the crowns according to their effect on stemflow; a class-A crown on a tree 14 inches in diameter, for example, has a much larger surface area exposed to rainfall than a class-A crown on a four-inch tree. Showing the effect of this inter-class correlation, the variations in both diameter and crown-class apparently exerted no influence on stemflow; the diameter-crown class interaction, however, proved significant (Table 4, A).

Stemflow was correlated well with storm-size in a positive straight-line relation, with spruce showing the weakest trend and pine the steepest regression-line (Table 4, B, and Fig. 3). Approximately 0.30 inch of rain was required to saturate the crowns and boles of the trees before stemflow could occur.

The different rates of stemflow from each species are probably due to the structure of their crowns. In general, branches of Engelmann spruce tend to slope downward from the bole toward the outer edge of the crown, thereby conducting water away from the bole and shedding it from the tips of the branches. In lodgepole-pine the reverse usually prevails; branches close to the bole are almost horizontal but toward the tips they curve upward rather sharply. Alpine-fir crowns are quite similar in structure to Engelmann spruce, but the branches usually have a less pronounced downward slope toward the crown-edge.

Summary of conclusions--Based on the data obtained, any of the four cutting methods resulted

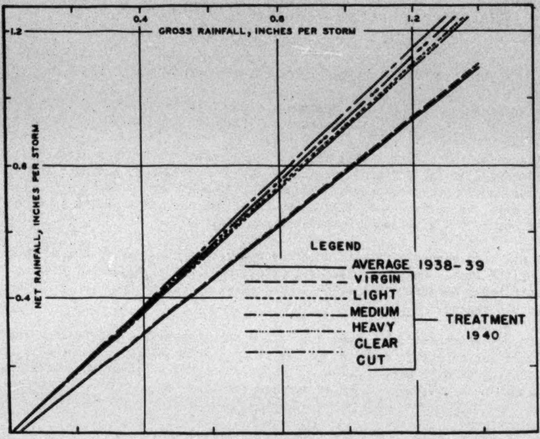


Fig. 3--Relation of stemflow to storm-size for three species of forest-tree

in augmented net rainfall and therefore a lowered rate of interception. Although this influence should be in approximate proportion to the intensity of treatment, no real correlation with treatments could be demonstrated in the present study. A negligible quantity of intercepted precipitation was returned to the soil by stemflow.

Net rainfall was found to be strongly related to gross precipitation per storm, with initial crown-storage and evaporation-rates during storms clearly expressed by the origins and slopes of regression-lines. Based on this analysis, most of the reductions in interception as a result of timber-cutting may be attributed to reduced evaporation during storm-periods.

Rocky Mountain Forest and Range Experiment Station,
Fort Collins, Colorado

PAPERS, SECTION OF HYDROLOGY

NATIONAL ACADEMY - RESEARCH COUNCIL BUILDING
SECOND SESSION, 2:00 P.M., MAY 1, 1941

APPLICATION OF THE INFILTRATION-THEORY TO ENGINEERING PRACTICE

L. K. Sherman and L. C. Mayer
(Presented by title)

Introduction--The objective of this paper is to furnish a working procedure to engineers whereby the principles of the infiltration-theory may be utilized to estimate the volumes of infiltration or surface-runoff from natural basins. While adhering to the basic principles of the infiltration-theory, the authors have used some approximations and averages in order to simplify the problem and reduce the time and labor otherwise involved.

This work has been made possible through the courtesy of the United States Corps of Engineers and the United States Department of Agriculture permitting the use of their data on rainfall, runoff, and their derived average loss-rates (f_{av}) on basins from 10 to 3,000 square miles in Oklahoma and Mississippi.

The methodology presented here makes use of a diagram whereby a progression-curve of average areal infiltration-capacity (f-curve) may be derived from any given value of f_{av}. The mass-curve of infiltration is discussed together with its practical application in finding the "index" of initial soil-moisture and the volumes of surface-runoff.

Symbols and definitions

f = infiltration-capacity of the soil
f_o = initial infiltration-capacity
f_c = ultimate infiltration-capacity
f_a = average infiltration-capacity for the storm-period
f-curve = progression-curve of infiltration-capacity from f_o toward or onto the line of f_c
Loss = the difference between the total depth of rainfall and the total depth of runoff
f_{av} = average loss-rate (It includes not only infiltration, but also interception, initial wetting, pocket-storage, evaporation during the storm-period, and other elements of loss which are more or less indeterminate on large natural basins.)
When f_{av} is used, the value of f in the corresponding f-curve will be slightly higher than those derived when f_a is used.
Locus = the single point on the f-curve where $f = f_{av}$
T = duration-time = loss/f_{av}

For further explanation of T and other terms, see L. K. Sherman, Derivation of f-curves from average loss-rates [Trans. Amer. Geophys. Union, p. 541, 1940].

The f-curve--The relation of infiltration-capacity f to the duration T of equivalent effective rain is shown by the f-curve. An f-curve may be constructed from any derived value of f_{av}, provided the value of f_c for the basin and the season is known.

The f-curve must meet the following requirements, illustrated in Figures 1 and 2:

(1) The f-curve at the locus "a" must be tangent to the line ac; ac is the hypotenuse of the triangle abc where ab = f_{av} (or f) and bc on the zero-base is always one hour.

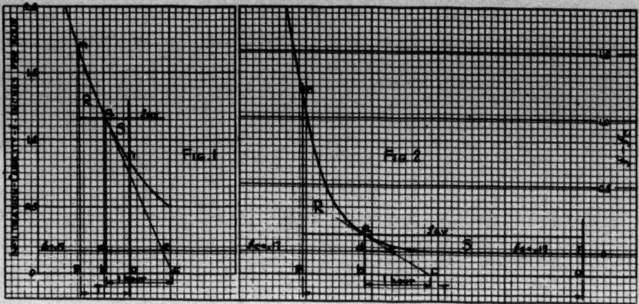
(2) The observed volume of loss must equal the volume indicated by the area under the f-curve (or its extension on line f_c) and the two vertical intercepts which are T hours apart (see area mnop).

(3) This observed volume of loss mnop may be divided into two parts: The volume above and the volume below the line f_c, namely, volume below = T × f_c and volume above = total observed volume of loss minus T × f_c.

(4) Within the limits of time T, the areas (volumes) R and S, above and below the horizontal line f_{av}, must be equal.

(5) The infiltration-capacity decreases with the duration of rainfall until an approximately constant minimum value f_c is reached. The progression-curve of infiltration-capacity shows a consistent decrease in values of f as the volume of infiltration increases.

In Figures 1 and 2, the triangle abc intercepts the f_c-line at points d and e, whence



Figs. 1 and 2--The f-curve

de/bc = ad/ab or $de/\ell = (f_{av} - f_c)/f_{av}$.

On the right of Figures 1 and 2, the locus and other points m and n are referred to a vertical scale with zero-base on the line f_c. Designate the base de as C_b.

This relationship

$$C_b = (f_{av} - f_c)/f_{av} \qquad (1)$$

together with the foregoing listed requirements (1), (2), and (3), permits the use of a convenient diagram for the derivation of f-curves applicable to any values of observed f_{av} on any basin, of any size, anywhere.

The C_b-diagram--Figure 3 shows a series of curves. Each curve is plotted to conform to the requirement that the tangent at any point on the curve with ordinate $(f - f_c)$ shall have the slope or inclination $(f - f_c)/C_b$. C_b is a constant for any particular curve with the base-value of C_b as designated at the top of the Figure. The curve at the left has a value of $C_b = 1.00$, or one hour. The other curves have fractional value of unity.

The locus point in Figure 1, referred to the f-scale (left), has a value of $f_{av} = 1.175$. If the value of f_c on this basin was 0.17, C_b in this case equals $(1.175 - 0.17)/1.175 = 0.855$. f_{av} on the right hand or $(f - f_c)$-scale is 1.005. This locus point of any such observed value of f_{av} can be plotted on the C_b-diagram at only one spot, namely, on the curve with a C_b-value of 0.855 and at the point on this curve where the ordinate $(f - f_c) = 1.005$.

All of the C_b-curves of the diagram start at time zero or the point PT. The volumes (inches of depth of infiltration) under each C_b-curve are indicated by the diagonal lines crossing the C_b-curves. Thus the volume under the curve 0.625, and above line f_c, at time 2.5 hours is 0.34 inch. The diagram as shown was derived graphically.

E. B. Escott, formerly Professor of Mathematics, University of Michigan, has derived the following equations which furnish a better means for plotting or extending the diagram.

$$\log (f - f_c) = \log B + \log e \, (x/C_b) = \log B + 0.4342945 \, (x/C_b) \qquad (2)$$

The value of constant B is 0.00945 or say 0.01 and log B = -2.0247736; x is time in hours from PT.

The volume or area under the curve and above the line f_c is

$$\text{Volume above } f_c = C_b \, (f - f_c - B) \qquad (3)$$

Derivation of an f-curve for a single storm on a basin--The basic data calls for a record of distributed hourly rainfall, the corresponding volume of surface-runoff, and the value of ultimate infiltration-capacity f_c for the given basin and season (growing or non-growing).

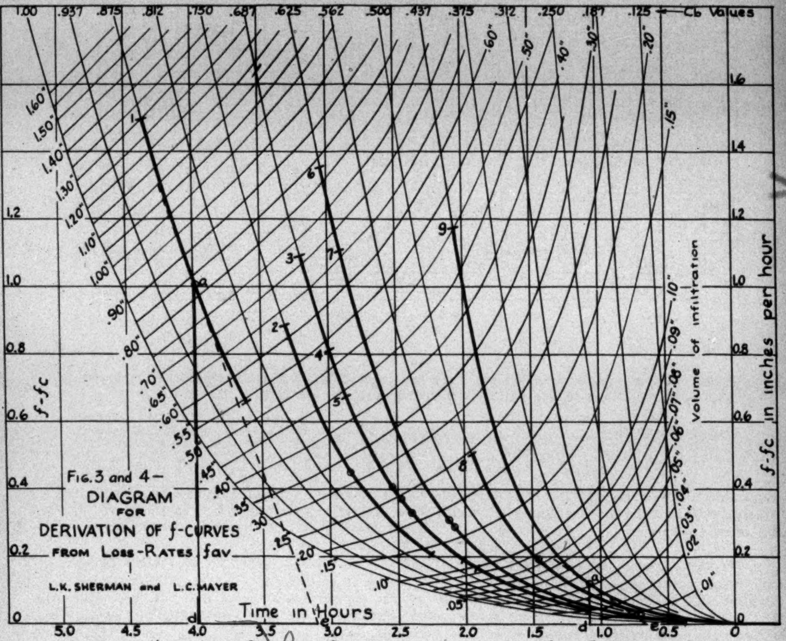


Fig. 3 and 4—DIAGRAM FOR DERIVATION OF f-CURVES FROM LOSS-RATES fav

L.K. SHERMAN and L.C. MAYER

HEAVY LINES SHOW ARCS FOR HUDSON AND CLEAR CREEK DATA-TALLAHATCHIE BASIN

(a) Derive f_{av} or the average loss-rate by the customary method of equating the volume of excess rain against the volume of runoff as described by Horton [Horton and Van Vliet, Derivation of average areal infiltration capacity from rainfall and runoff data, U. S. Dept. Agric., Office of Land Use Coordination, Flood Control, Washington, D. C., mimeographed November 1940]. Find T = volume of loss/f_{av}.

(b) Find C_b according to equation (1) and select the curve C_b on the diagram.

(c) Locate the locus point on this curve.

(d) Find the volume of loss above the line f_c as heretofore described.

(e) Get the time-position of beginning and ending of the f-curve. To do this proceed as follows: Scale off the length T, on a sheet of paper, to correspond with the time-base of the diagram. Center this T-scale near the locus point and note the two volumes intercepted on the given C_b-curve by the verticals at each end of T. The difference between these two volumes must equal (d) the specified volume above f_c. Move the scale T to the right or left until it does equal (d). Under this condition the left-hand intercept of T gives the location of f_0 and its time-position with respect to zero-time on the diagram. This arc of the f-curve may be transposed or traced onto a sheet with ordinates of f and the time-scale laid off in the usual manner from the left and increasing toward the right.

We will illustrate the foregoing with derivation of f-curves from data on the basin of Tallahatchie, Mississippi.

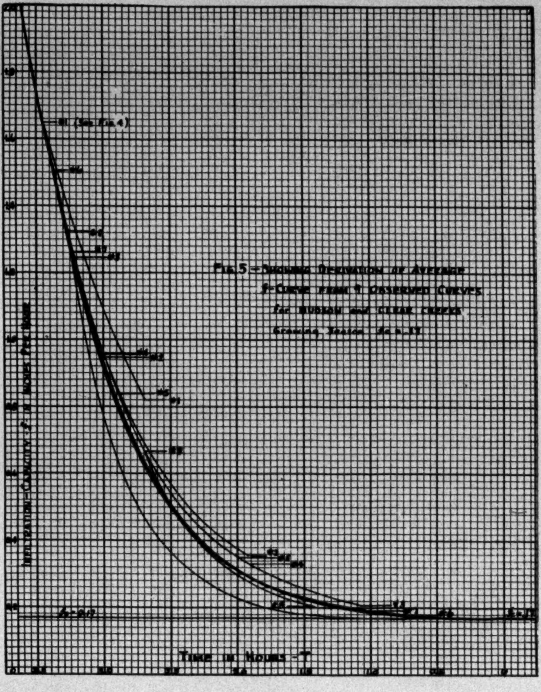


Fig. 5--Showing Derivation of Average f-Curve from 9 Observed Curves for Hudson and Clear Creeks Growing Season f_c=.17

Case 1--Hudson Creek; June 12-13, 1939; growing season f_c = 0.17; rain = 1.22 inches and runoff = 0.333 inch; T = 0.75 hour; f_{av} = 1.175 inches

Volume-loss = 1.22 - 0.333 = 0.887 inch
Volume below f_c is f_c × T = 0.17 × 0.75 = 0.127 inch
(d) Volume above f_c = 0.760 inch
(b) C_b = (1.175 - 0.17)/1.175 = 0.855 (use nearest curve or 0.875)
(c) The locus point (f - f_c), or 1.005, is at time 3.98 hours on the diagram. The position of T = 0.75 on each side of the locus to intercept the volume (d) or 0.76 inch is
t at left = 4.37 hours (f_o) and volume = 1.30 inches
t at right = 3.62 hours (f_o) and volume = 0.54 inch
T = 0.75 hour Volume above = 0.76 inch (see 1 of Fig. 4)

Case 9--Clear Creek; June 17, 1939; growing season f_c = 0.17; rain = 1.87 inches and runoff = 0.649 inch; T = 4.23 hours; f_{av} = 0.289 inch

Volume-loss = 1.87 - 0.649 = 1.221 inches
Volume below f_c is f_c × T = 0.17 × 4.23 = 0.720 inch
(d) Volume above f_c = 0.501 inch
(b) C_b = (0.289 - 0.17)/0.289 = 0.412 (use nearest curve on diagram or 0.437)
(c) The locus point (f - f_c), or 0.119, is at time 1.08 hours on the diagram. The position of T = 4.23 on each side of the locus to intercept the volume (d) or 0.501 inch is
t at left = 2.06 hours (f_o) and volume = 0.501
t at right =+2.17 hours (f_o) and volume = 0.000
T = 4.23 hours Volume above = 0.501 inch (see Fig. 4)

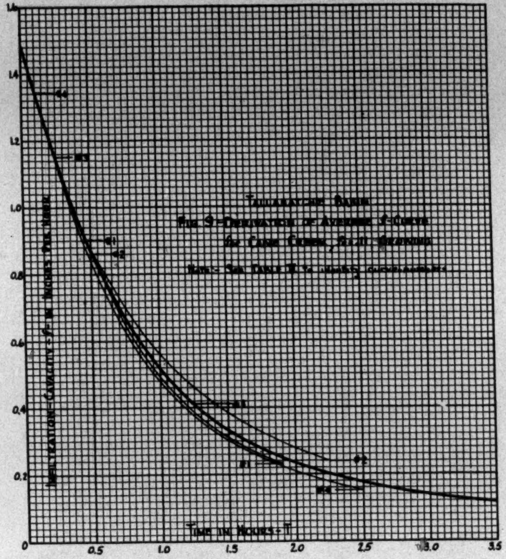
Table 1--Little Tallahatchie River-Basin

Storm No.	Drainage-basin	Storm-period		Rain-fall, inches	Run-off, inches	Volume-loss, inches	f_{av}, hours	Time, hours	f_c used
Fig. 5; growing season; area 9.35 square miles; soil, brown loam									
6	Hudson Creek	May 17-18, 1939		1.33	0.053	1.277	0.478	2.67	0.17
1		June 12-13, 1939	Peak 1	1.22	0.333	0.887	1.175	0.75	
4			Peak 2	0.71	0.100	0.610	0.575	1.06	
3		June 16-18, 1939		1.34	0.285	1.055	0.499	2.12	
2		June 26-27, 1939		0.69	0.022	0.668	0.620	1.07	
Fig. 5; growing season; area 9.30 square miles; soil, brown loam									
8	Clear Creek	Apr. 26-27, 1939		0.85	0.401	0.449	0.352	1.26	0.17
5		June 12-14, 1939		1.10	0.625	0.475	0.543	0.87	
9		June 17-18, 1939		1.87	0.649	1.221	0.289	4.23	
7		June 26-27, 1939		1.12	0.092	1.028	0.464	2.22	
-		June 27-28, 1939		0.97	0.716	0.254	0.179	1.42	
Fig. 12; dormant season; area 23.9 square miles; soil, Pontotoc Ridge									
1	Upper Tallahatchie	Mar. 26-28, 1939		1.20	0.284	0.916	0.253	3.62	0.08
2		Apr. 11-12, 1939		2.20	0.750	1.45	0.43	3.38	
3		Mar. 11, 1940		0.712	0.124	5.88	0.286	2.05	
4		Mar. 12, 1940		1.15	0.470	0.68	0.338	2.01	
-		Mar. 12-13, 1940		0.939	0.472	0.467	0.094	4.98	
Fig. 11; growing season; area 11.14 square miles; soil, flatwoods and Pontotoc Ridge									
1	Lukesasper Creek	May 18-20, 1939		1.36	0.048	1.312	0.74	1.78	0.09
2		June 22-24, 1939		1.11	0.192	0.918	0.914	1.00	
3		June 26-28, 1939		1.35	0.778	0.572	0.182	3.126	
4		June 29-31, 1939		0.75	0.324	0.426	0.434	0.99	
-		June 16-19, 1939		3.36	2.593	0.767	0.09	8.49	
Fig. 13; dormant season; area 27.35 square miles; soil, clay hills									
1	Hell Creek	Mar. 26-Apr. 2,1939	Peak 1	1.60	0.494	1.106	0.260	4.23	0.05
2			Peak 2	1.96	1.371	0.589	0.078	7.76	
3		Apr. 10-14, 1939		1.40	0.751	0.649	0.144	4.51	
Fig. 14; growing season; area 27.35 square miles; soil, clay hills									
1	Hell Creek	May 21-23, 1939		3.92	2.386	1.534	0.30	5.12	0.09
2		June 26-28, 1939		1.82	0.589	1.231	0.384	3.20	
3		July 27-29, 1939		2.47	0.850	1.62	0.888	1.82	
4		Aug. 9-10, 1939		1.17	0.255	0.915	1.03	0.88	
-		June 16-20, 1939		3.69	2.743	0.947	0.09	10.53	
Fig. 9; growing season; area 23.80 square miles; soil, flatwoods and Pontotoc Ridge									
1	Cane Creek	May 18-20, 1939	Peak 1	0.71	0.049	0.661	0.469	1.41	0.11
2			Peak 2	0.74	0.129	0.611	0.360	1.71	
3		June 11-14, 1939	Peak 1	1.88	1.269	0.611	0.568	1.06	
4			Peak 2	2.68	1.549	1.131	0.460	2.41	
-		June 17-18, 1939		3.11	1.813	1.297	0.132	9.83	
Fig. 10; dormant season; area 23.80 square miles; soil, flatwoods and Pontotoc Ridge									
1	Cane Creek	Mar. 11-15, 1940	Peak 1	0.72	0.179	0.541	0.314	1.72	0.07
2			Peak 2	1.25	0.761	0.489	0.167	2.93	
3		Apr. 4- 5, 1940		2.60	1.509	1.091	0.308	3.53	
-		Mar. 11-15, 1940	Peak 3	1.20	0.769	0.431	0.080	5.38	

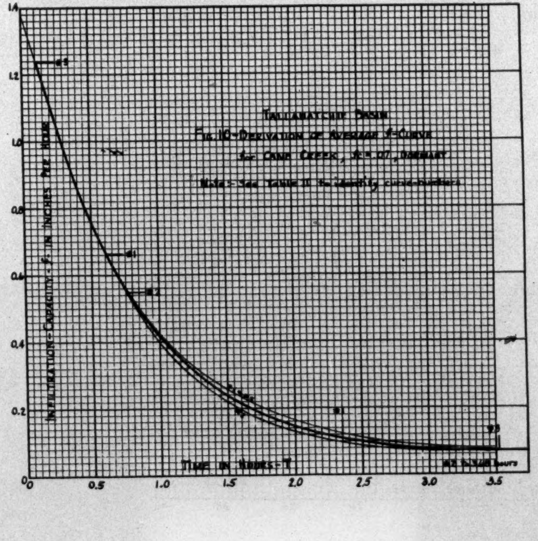
If a special diagram were constructed so that the volume-lines included the amounts of both above and below f_c, the derived time-positions t would be the same as the foregoing cases (e).

Averaging of f-curves--On the C_b-diagram in Figure 4, we have noted seven other f_{av}-observations on the Hudson-Clear basins in addition to the two cases 1 and 9 heretofore discussed.

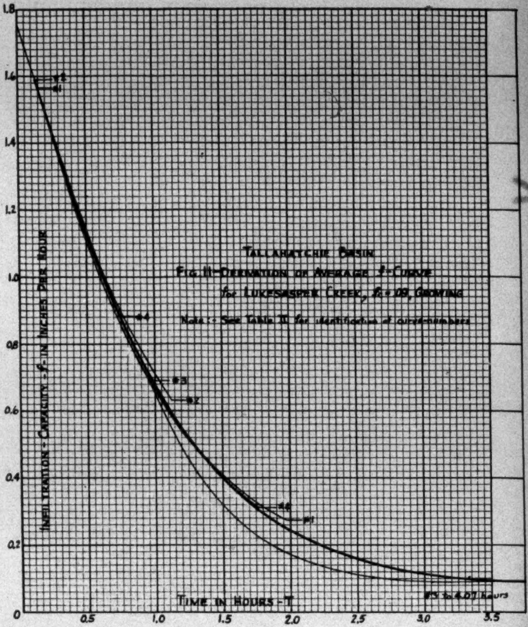
Figure 5 shows all of these curves or arcs traced from Figure 4 and assembled, at their individual starting points (or f_0) against the longest f-curve with a high value of f_0, namely, Case 6. The average f-curve for all of the data is shown by the heavy line in Figure 5.



TALLAHATCHIE BASIN
FIG. 9–DERIVATION OF AVERAGE f-CURVE
for CANE CREEK, f_c=.11, GROWING
NOTE:- See TABLE II to identify curve-numbers

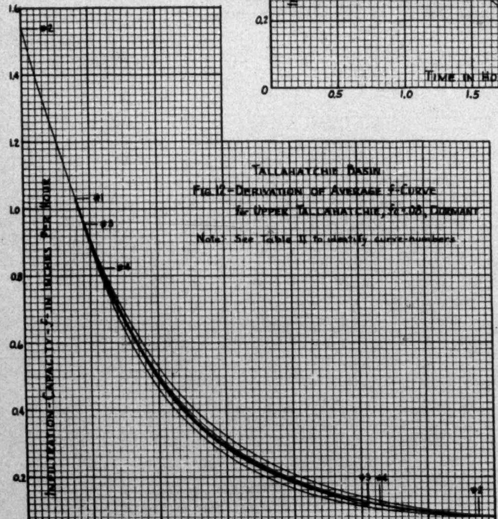


TALLAHATCHIE BASIN
FIG. 10–DERIVATION OF AVERAGE f-CURVE
for CANE CREEK, f_c=.07, DORMANT
NOTE:- See TABLE II to identify curve-numbers



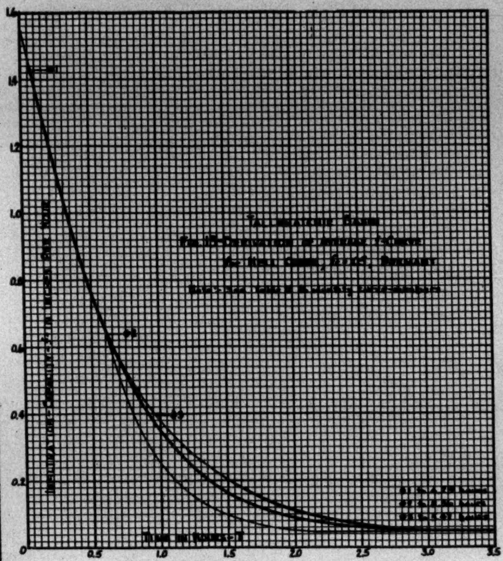
TALLAHATCHIE BASIN
FIG. 11—DERIVATION OF AVERAGE f-CURVE for LUKESASPER CREEK, f_c = .09, GROWING

Note:- See Table II for identification of curve-numbers

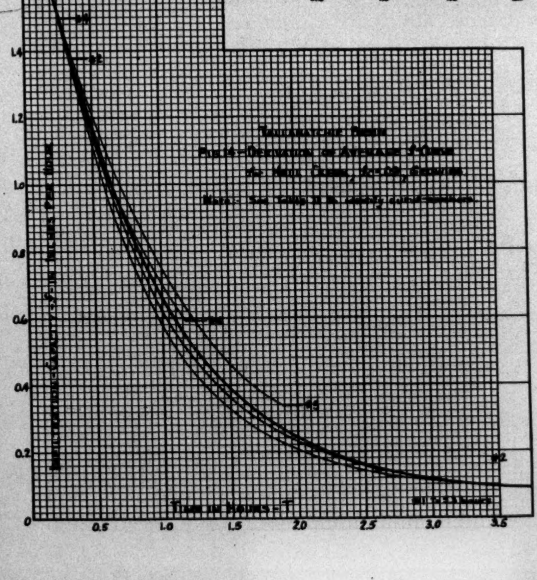


TALLAHATCHIE BASIN
FIG. 12—DERIVATION OF AVERAGE f-CURVE for UPPER TALLAHATCHIE, f_c = .08, DORMANT

Note: See Table II to identify curve-numbers

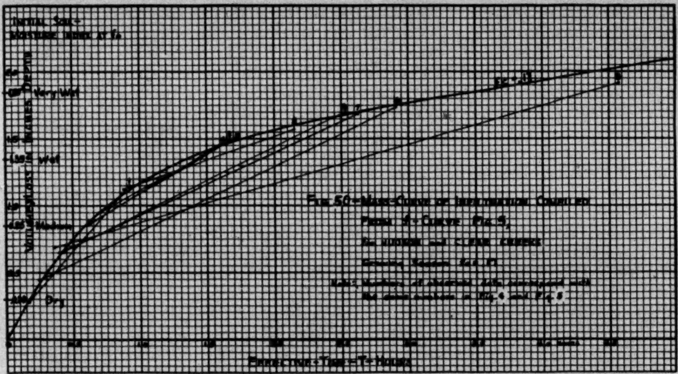


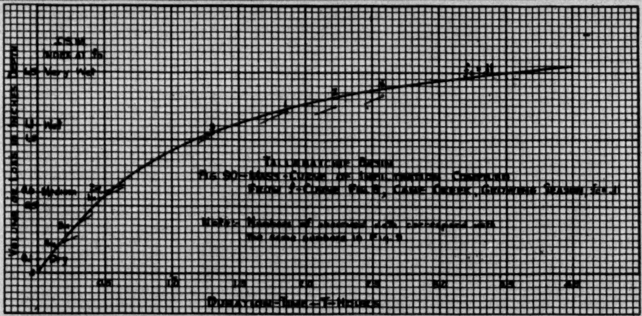
Tallahatchie Basin
Fig. 15-Derivation of Average f-Curve
for Hell Creek, f_c=0.05, Dormant
Note:- See table II for identity curve numbers

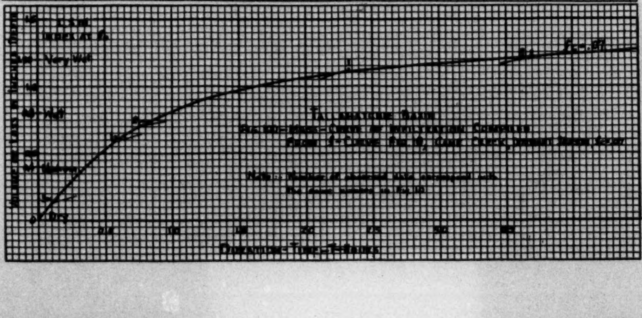


Tallahatchie Basin
Fig. 14-Derivation of Average f-Curve
for Hell Creek, f_c=0.10, Growing
Note:- See Table II for identity of curve numbers.

Tallahatchie data, Table 1--The following data on basins of the Little Tallahatchie were applied to the derivation of Figures 5, 9, 10, 11, 12, 13, 14, and their mass-curves. It was made available through permission of the United States Department of Agriculture. The Little Tallahatchie Basin of Mississippi includes all of the tributary basins noted herein. About 75 rain-gage stations were in operation on the Little Tallahatchie Basin in the latter part of 1939. In the fall of 1939 some 14 of these were recording rain-gages and the number was increased in 1940. Stage-recorders were operated on all of the branch streams noted herein. The data here presented were collected and analyzed by the Little Tallahatchie Flood-Control Survey Party under





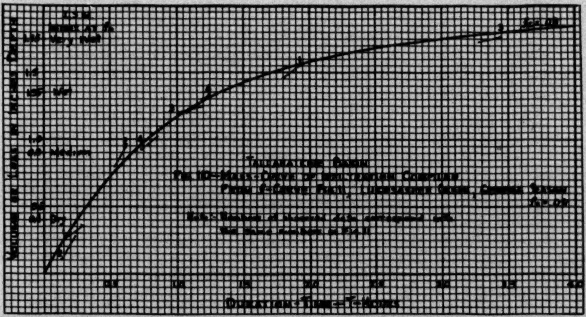


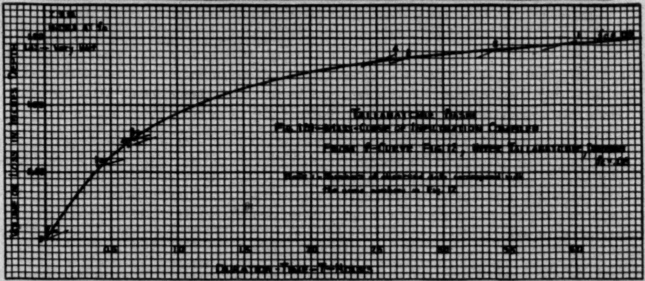
the leadership of the United States Forest Service.

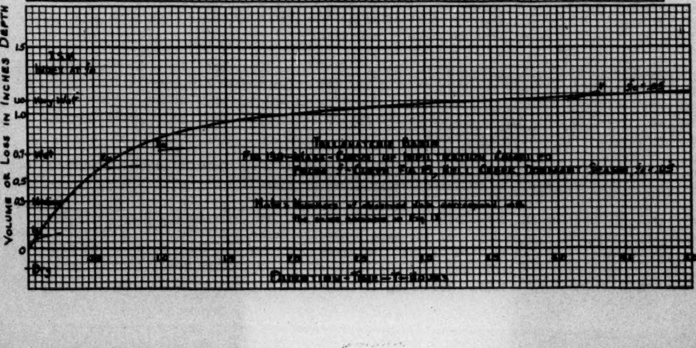
Some of the data are more reliable than others. However, the data have been carefully checked. Geographical variations in rain-intensity are not excessive. We have found few inconsistencies in the derived f-curves.

Ultimate infiltration-capacity (f_c)

Data on f_c for the Little Tallahatchie basins--A study of the Little Tallahatchie data indicates that the following values of f_c are reasonable and consistent.







Example 1--Cane Creek, storm of March 10, 1939, dormant season, $f_c = 0.07$

Weighted[a] hourly rain on basin, inch	Initial soil-moisture index "Dry", .10 on Fig. 100	Computed with f, Fig. 100	Computed runoff, inch
0.01	0.11	0.73	0.0
0.01	....	....	0.0
0.15	....	....	0.0
0.16	....	....	0.0
0.02	0.45	....	0.0
0.31	0.76	0.50	0.0
0.62	1.03	0.27	0.35
0.05	1.08	0.11	0.0
0.00	....	....	0.0
0.01	....	....	0.0
0.01	....	....	0.0
0.06	1.16	0.08	0.0
0.06	1.22	0.07	0.0
0.06	....	0.07	0.0
0.05	....	0.07	0.0
0.05	....	0.07	0.0
0.07	....	0.07	0.0
0.04	....	0.07	0.0
0.03	....	0.07	0.0
0.04	....	0.07	0.0
0.04	....	0.07	0.0
1.82	Totals		0.35
	Observed runoff = 0.36 inch		

[a] Weighted average hourly rain computed by authors with Thiessen's method.

Soil of Basin	Growing season Apr. to Sept.	Dormant season Oct. to March
Brown loam	0.17	0.08
Clay-hills	0.15	0.07
Pontotoc	0.11	0.07
Flatwoods	0.08	0.03

The storms with the largest values of T furnish the lowest ultimate figures for f_c. The terminal time for shorter storms indicates somewhat higher values than those in the accompanying tables. This may mean that f_c should be a very flat concave curve instead of a straight line. For practical purposes the use of a single f_c -figure seems admissible on large areas.

Mass-infiltration curves

The volume of infiltration (loss) for any f-curve, for any time-period, is indicated by the summation of the f-ordinates multiplied by a short increment of time $(t - t_1)$. Accompanying are mass-curves compiled from the average f-curves shown in Figures 5, 9, 10, 11, 12, 13, and 14. The mass-curve Figure 50 refers to its f-curve Figure 5; Figure 90 refers to its origin Figure 9, and so on.

The mass-curves were plotted with zero-volume and zero-time corresponding to the highest point on the observed f-curve. The use of the average mass-curve for a given basin and value of f_c calls for no specific starting-point figure. It may be 0, 80, or any other figure, since only differences in time or volume are made use of. An adjustment of the zero-points for approximate correlation can be made if desired. This adjustment may be useful. In any event, it is harmless.

Check on the procedure--The mass-curve should agree with all of the observed values of f_{av} applicable to the basin, if the procedure and the data are correct. Any f_{av} may be represented graphically by a right-angle triangle with time T as base and volume of observed loss as altitude. The position of the lower point on the hypotenuse of the f_{av} triangle is known. It is on, or may be plotted on, the sheet of f-curves and has a fixed relation to the zero-point. Hence the intervening volume of infiltration from zero is known and hence the position of this low point of the f_{av} may be plotted on the mass-diagram. This fixes the position of the upper point of the triangle with respect to the mass-curve. If the data and the procedure are correct, the point will fall upon the mass-curve. In this manner a number of pairs of f_{av}-points have been plotted. In so plotting one-half the error has been charged to the upper point and one-half to the lower. The results speak for themselves.

Antecedent soil-moisture index--The notations "wet", "medium", and "dry", and corresponding figures on the mass-curves were obtained by dividing the total volume of infiltration, from zero to tangency with the f_c-line, into four parts. "Dry" is at one-fourth, "medium" at one-half, and "wet" at three-fourths. This is a tentative rating and can be modified by field-observations as to relative initial soil-moisture.

The actual index-figure for any antecedent soil-moisture condition for an observed storm can be found on the mass-diagram. An illustration is given by Example 1.

In Example 1, the runoff, 0.36 inch, is known. The problem is to find the relative initial soil-index on mass-curve Figure 100. By the same procedure described herein for Hudson and Clear Creek basins, Figures 4 and 5, we find by the C_b-diagram that the locus was on C_b-curve 0.750, $f_{av} = 0.28$, volume above $f_c = 1.07$, and that the value of $(f - f_c)$ corresponding to volume 1.07 on curve 0.750 is 1.30 or $f_o = 1.37$. Referring to f-curve of Figure 10, we find that this f_o is

Example 2--Cane Creek, storm of June 17, 1939, $f_c = 0.11$

Weighted[a] hourly rain on basin, inch	Initial soil-moisture index taken as 1.38 inches, Fig. 90	Computed with f, Fig. 90	Computed runoff, inch
	1.38		
0.083	1.463	0.30	0.0
0.182	1.645	0.27	0.0
0.396	1.815	0.17	0.226
0.586	1.925	0.11	0.476
0.712	.....	0.11	0.602
0.542	.....	0.11	0.432
0.083	.....	0.11	0.0
0.0	.....	0.11	0.0
0.021	.....	0.11	0.0
0.038	.....	0.11	0.0
0.020	.....	0.11	0.0
0.013	.....	0.11	0.0
0.0	.....	0.11	0.0
0.0	.....	0.11	0.0
0.039	.....	0.11	0.0
0.157	.....	0.11	0.047
0.102	.....	0.11	0.0
0.141	.....	0.11	0.031
0.047	.....	0.11	0.000
3.16	Totals		1.814
	Observed runoff = 1.81 inches		

[a] Weighted average hourly rain computed by authors with Thiessen's method.

somewhat higher (and drier i.s.m.) than the established or known point 3. We therefore note on mass-curve Figure 100 that the initial soil-index is lower than 0.15 inch given for 3. We try index-number .10 and find that the computed runoff 0.35 inch checks with the observed runoff.

Derivation of the volume of surface-runoff from hourly rainfall and the mass-curve of infiltration for the Basin--The solution of this problem is required by engineers for estimating runoff from real or hypothetical storms.

In Example 2 for storm of June 17, 1939, we are to find the volume of runoff prior to any stream-flow observations. We first refer to the data in Table 1. We find that there were heavy rains on June 13-14, which made "very wet" soil. We also note that a two- or three-day drying spell intervened before the storm of June 17 and that high rates of evaporation and transpiration probably took place. We conclude that the antecedent soil-moisture has been reduced from "very wet" to "wet".

Referring to mass-curve Figure 90, we select an index-figure one point drier than wet, namely, 1.0 (or, on the correlated scale, 1.38). The value of f for the first hour of storm of June 17 is 0.30, as shown in the Example. This value of f decreases until the constant f_c of 0.11 is reached.

For further examples, see L. K. Sherman, The unit hydrograph [Bull. Assoc. State Eng. Soc., 317 Fifth Street, Ames, Iowa, April, 1941].

Comments

(1) The type of f-curve, or C_b-curve, in the diagram was chosen because it fits fairly well with observed f-curves and furnishes a mass-curve which conforms to the observed data. All locus points to be used with the diagram should be more than 0.05 above the f_c-line. The point of tangency to the line f_c has wide time-limits with very slight changes in volume above f_c.

(2) The individual f-curve of a group seems to be more concave as the locus f becomes smaller. There is evidence that this is a natural law. We have adopted an average curve of a group because the results gave close agreement with all the data and also simplified the problem.

(3) The accurate forecasting of the initial soil-moisture index calls for further study. The mass-curve furnishes a means for correlation with observed antecedent meteorological conditions.

(4) The mass-curve furnishes a simple means for deriving runoff from any sequence of hourly rainfall. If the antecedent soil-moisture index is correctly taken, the derived runoff will be correct within a small percentage of error.

Similar studies are being made on data from the Great Salt Plains region of Oklahoma.

Chicago, Illinois

METHODS FOR THE MEASUREMENT OF INFILTRATION

H. G. Wilm
(Presented in abstract by C. H. Diebold)

The measurement of infiltration has, in recent years, assumed increasing importance as a means of estimating the relative absorptive capacities of soils under different vegetal types or kinds of land-use. The utility of infiltration-criteria rests partly on the assumption that surface-runoff in any appreciable volume is deleterious and that it results in movement of soil and in excessive peak-rates of stream-flow. Based on this assumption, a land-use providing maximum infiltration-capacities may be considered optimum for retention and storage of precipitation. In hydrologic investigations, too, a knowledge of relative infiltration-indices may assist greatly in the synthesis of hydrographs, or in the estimation of expected rates of flood-flow in streams. In watershed-management studies, infiltration-indices obtained for soils under several types of plant-cover and land-use are helpful in providing a basis for judgment as to optimum watershed-conditions for water-yield and erosion-control.

Problems in the measurement of infiltration

In general, two distinct methods of attack have been applied to the appraisal of watershed infiltration-capacities. In the first, extensively used by hydrologists with varying success [see 3, 4, 5, 7, 12, 13 of "References" at end of paper], watershed infiltration-indices are obtained by analysis of stream-hydrographs. This method obviously provides indices only for complete drainage-units and often fails to lend itself to appraisal of the relative importance of various types of land-use in regulating infiltration.

The second general approach involves the use of artificially sprinkled plots with portable equipment [1, 2, 6, 8, 9, 10, 11]. Because of its inherent flexibility, this method may be easily disposed to fit any desired design for experiments or watershed-surveys. As frequently found in new investigations, a number of instruments have been devised for infiltration-studies, employing a wide variety of plot-sizes and methods of sprinkling. Two types of equipment (the Soil Conservation Service type-F and type-FA plots) are being widely used in flood-control surveys, although as yet no conclusive proof has been offered as to the advantage of these apparatus over other types.

Apparently, the dominant characteristic of plot-measurement of infiltration is its great variability. Even acknowledging the fact that plot-data must be relative rather than quantitative in nature, studies made in different regions, or with different instruments, show excessive variation and some discrepancies in results. Often, the variability of measurements even within a relatively homogeneous soil or plant-cover type is so great as to impose serious doubt upon the validity of average infiltration-indices.

Objectives of the investigation

In order to provide at least a partial solution to problems in the measurement of infiltration by sprinkled plots, this series of experiments was designed to accomplish three specific objectives: (1) To determine the relative reliability of various instruments in common use; (2) to evaluate the comparative importance of various factors such as "rainfall"-intensity, soil-temperature, and characteristics of the soil and plant-cover which might logically be expected to influence infiltration; (3) to suggest efficient methods of attack for future experiments or surveys, which should successfully isolate and control at least the more important sources of variation, and should provide maximum accuracy and efficiency in the appraisal of infiltration as measured by sprinkled plots.

It is recognized that, under the first two of these objectives, any single investigation may yield results of only local application. Since, however, this study is rather new in conception as applied to its particular field, even the general trends which have been discovered, together with the universally applicable principles of experimental design, may prove to be of justifiable value to future workers in the field of infiltration.

Scope of experiments

Location--All experimental work was done during the summer of 1940 in a valley of the Rocky Mountain Front Range, about 27 miles northwest of Colorado Springs, Colorado. The area studied is part of the Manitou Experimental Forest, a research center for investigations in watershed- and range-management maintained by the Forest Service. The valley, about 7,600 feet in elevation, is relatively gentle in topography, with slopes varying from two to 35 per cent or occasionally more. Although naturally range-land, covered with a native growth of bunchgrass (Muhlenbergia montana and Festuca arizonica) and associated species, much of the area has been cultivated.

In general the soils, derived from Pikes Peak granite, Sawatch sandstone, and Manitou limestone, are very coarse and gravelly. Partly because of their high feldspar-content, however, the content of coarse gravel is much reduced by continuous cultivation and exposure to weathering. Where vegetation is thin or absent and soil-losses have occurred, a distinct "erosion-

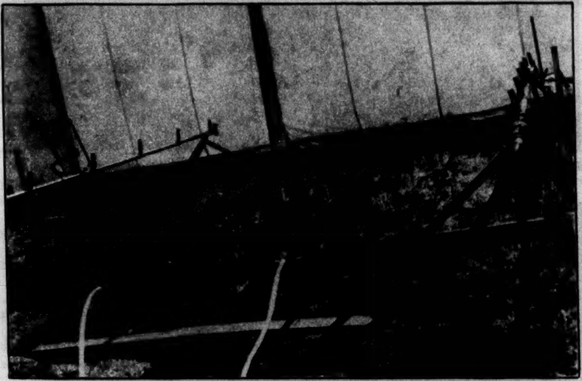


Fig. 1--Modified type "F" plot, with trough rain-gage in place [Runoff is collected in the covered trough (foreground) and conveyed to a collector tank]

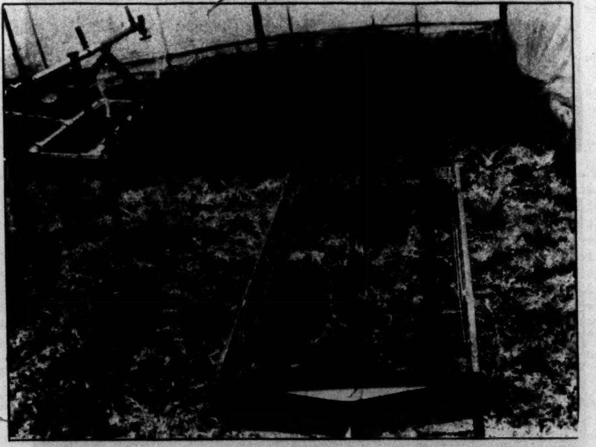


Fig. 2--Rocky Mountain equipment in operation (Sprinklers at upper left apply water at rate of approximately four inches per hour, measured in battery of 12 small rain-gages; runoff is collected at nearest end of plot)

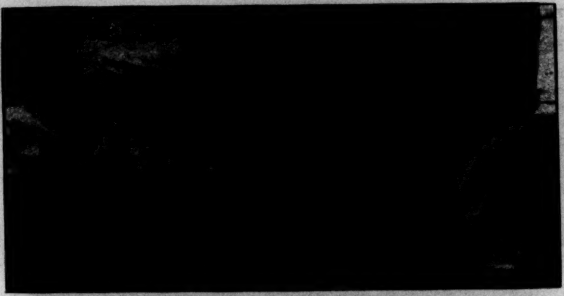


Fig. 3--Modified North Fork plot in an abandoned field [Sparseness of vegetation is in marked contrast to conditions in valley bunch-grass (Fig. 2)]

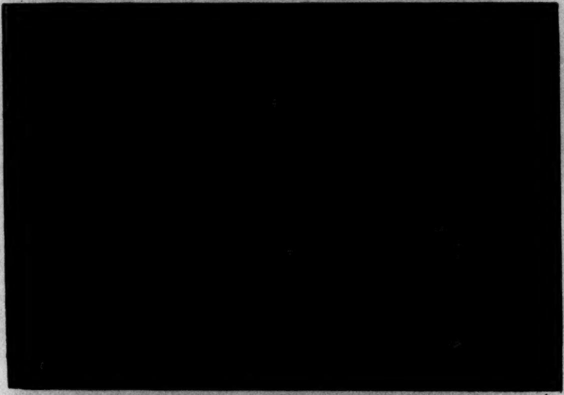


Fig. 4--Square-foot plot, with water applied through perforated pipe along right edge of frame; runoff is collected at the left

Fig. 5--General view of single group of infiltration-plots, set up in valley bunch-grass type (Arranged from left are a Rocky Mountain plot, a type "F" plot, and modified North Fork equipment; the square-foot plot is not visible; when closed, the canvas shelter gave adequate protection from ordinary winds) pavement" of coarse gravel often occurs on the soil-surface.

The climate is typical of the mountainous Front Range of Colorado. About 80 per cent of the yearly total precipitation falls between April and September 30--most of this amount in the form of rain and often in storms of high intensity.

Instruments studied

Five types of instruments were employed, each of which has been more or less commonly used for the measurement of infiltration:

(1) Type-F infiltrometer (modified)--Specifications were obtained from the Soil Conservation Service for this type of equipment, and modified slightly in construction. The plot-frame is 6.6 by 12 feet in dimensions (Fig. 1). Rainfall was measured in two trough gages, each 12 feet long and one inch wide, placed parallel to the long axis of the plot and along lines bisecting the right and left halves of the plot. This method was considered to provide improvement over the use of pans or tarpaulins for measuring precipitation before and after each infiltration-test, which fail to give a record of water actually applied during the test. Water was applied by a motor-driven pump through 13 type-F sprinklers, placed according to Soil Conservation Service specifications. Runoff-water, passing through a screened collector trough, was measured by an electric point gage in a calibrated container.

(2) Rocky Mountain infiltrometer--This plot is bounded by a rigid, non-adjustable frame, 2 by 4 feet in dimensions (Fig. 2). Water was applied by three type-F sprinklers, from the same pump which furnished precipitation for the type-F and modified North Fork equipment. After some experiments with methods for measuring precipitation-rates, a group of 12 circular rain-gages was adopted, providing a rainfall-sample of one per cent of the plot-area. These cans, each one inch in diameter (inside) and four inches tall, were strung on wires tightly drawn over an angle-iron frame. The frame and gages were available in duplicate, to facilitate rainfall-measurements by alternate use during a test-run. The catch in all gages was read in a single graduate, to provide an average rainfall-figure for the plot. Runoff passed through a collector trough into an eight-inch collector can; volumes were measured in a 1,000-cc glass graduate.

(3) Modified North Fork equipment--This plot resembles the Soil Conservation Service type-FA infiltrometer, with an area of 2.5 square feet (Fig. 3). Water applied through two type-F sprinklers was measured by means of six rain-cans, each one inch in diameter; runoff was measured in 1,000-cc graduates.

(4) Pearse square-foot apparatus--As indicated in Figure 4, this equipment consists of a light frame one foot square, with a runoff-plate along the lower edge. Water was applied from a graduated container to the upper edge of the plot through a perforated pipe. Water applied and runoff were measured in cubic centimeters.

Organization and field-procedure

The whole series of field-experiments was divided into two main steps, preceded by a careful calibration of all plot-equipment, including a study of the accuracy of rain-gages used to measure "rainfall", or the volumes of applied water. The first actual study of infiltration (hereafter called "initial study") included measurements by all four instruments discussed above, taken on 30 different sites in the bunchgrass cover-type. While the four types of equipment were grouped together at each site in order to minimize environmental variation within the site, local variation was subjected also to statistical control by measurement of a number of concomitant factors: "Rainfall"-intensity; soil-temperature during the test; ground-slope; plant-cover density; and gravel-content of the soil. All tests were made on "wet" soil; four hours before the experimental run on each site, the whole area was sprinkled for 15 minutes at a rate of four inches of rainfall per hour. All equipment was protected from wind by a canvas shelter (Fig. 5). In each run, water was applied for 50 minutes at a rate of approximately four inches per hour, with measurements of rainfall and runoff at ten-minute intervals.

Finally, a second complete infiltration-experiment was conducted to check the results of the initial study. In this case, for the sake of compactness, only the three smaller infiltrometers were used, and variability within each site was controlled by replication of each method in a 3 by 3 "Latin square" [14] on each study-site. By the use of Latin squares, even the natural variations within a single site could be partly isolated; since each infiltration-instrument occurred once in each row and column of each square, any differences in infiltration between rows or columns were free of instrumental variation and represented only variability of site. In this final study, measurements were taken on six sites in each of two plant cover-types, including abandoned agricultural fields as well as the bunchgrass-type. All sites were chosen on a ground-slope of 15 per cent. Again, a group of concomitant factors was measured to provide statistical control of otherwise unregulated variants. In the field-work, one whole row was tested simultaneously, with water applied for 50-minute intervals; all three rows in a single site were run in one day. After each day's tests, a new site was laid out and wetted by sprinkling, as in the first infiltration-study. All other field-procedure resembled that for the initial study, except that soil-samples were taken for volume-weight determination as well as for gravel-content. The volume-weight samples were obtained by driving a four-inch steel cylinder into the soil, removing its soil-contents, and measuring the excavated volume by refilling the cavity with a measured quantity of sifted, dry sand. Four samples were taken in each Rocky Mountain plot, two in the North Fork plot, and one in each square-foot plot.

Characteristics of data

Rainfall--The figures used in analysis were those secured during the last 20 minutes of each 50-minute infiltration-test. Based on results of the preliminary rain-gage calibration, rainfall-data for the Rocky Mountain and North Fork plots were corrected for consistent deviation of rain-gage measurements from the total volumes of water applied. All values were expressed in inches per hour.

Infiltration--Data for this variable were obtained by subtracting runoff during the last 20 minutes from the volume of water applied during the same period, after correcting for "lag". The resulting figures were expressed in inches per hour.

Soil-temperature--These values were average temperatures in degrees Fahrenheit, taken one-half inch below the soil-surface on each plot during the last 20 minutes of each test.

Gravel-content of soil--For each combined sample on each plot, a sieve-analysis was used to determine the percentage of the total oven-dry sample composed of particles larger than 0.149 mm.

Volume-weight of soil--Used only in the Latin-square study, these data were the oven-dry weights of samples taken for each instrument, expressed in grams per cubic centimeter of original volume.

Plant cover-density--On each plot, the total density of living and dead organic material was estimated ocularly, and expressed as a percentage of the total plot-area.

Ground-slope--In the initial study, the slope of each plot was expressed in per cent; all plots were established on a slope of 15 per cent in the Latin-square study.

Results and discussion

The data for both studies were analyzed by the methods of variance and covariance [14], accompanied by examination of simple and adjusted averages and statistics of variation.

When average infiltration-rates obtained by the various infiltrometers are compared (unadjusted averages in Table 1), the immediate impression is one of striking variability between methods, and even between results obtained in the two separate studies for any single method. Since no absolute value of infiltration can be known for the soil on which these tests were made, the amount of variation observed among the methods can only result in a feeling of uncertainty as to the validity of any of the results. When, however, consideration is given to the natural heterogeneity of any soil, it is apparent that this factor alone may induce variability in results, since even a single type of instrument used on different sites is exposed to variations in soil-permeability. A comparison of different instruments is exposed to similar discrepancies; any indicated difference between infiltrometers must include some variation of site as well as actual differences between methods. The variability of infiltration from site to site is clearly shown by the "mean squares" for each of the instruments in the initial study (Table 2). From these data--the squared standard deviations for each method--can be computed their standard deviations, the standard errors of averages obtained with any number of observations, or the number of plots needed to provide any desired standard of accuracy. For the purpose of this study it is unnecessary to go beyond the mean squares themselves, however, as these statistics express directly the relative variability of the several infiltrometers. The Rocky Mountain and modified North Fork instruments are approximately equal in variability, for example, while the square-foot plot is about 3-1/2 to 4 times as variable as the other two methods. In other words, four times as many square-foot plots are needed to provide averages as "reliable" as those ob-

Table 1--Average infiltration-rates by four infiltrometers

Method	Initial study		Latin-square study[a]	
	Unadjusted, inch/hour	Adjusted, inch/hour	Unadjusted, inch/hour	Adjusted, inch/hour
Type "F"	2.793	3.513	.....	.....
Rocky Mountain	2.110	2.110[b]	1.471	1.754
Modified North Fork	1.781	2.463	1.636	1.931
Square-foot	3.115	1.746	2.113	1.534

[a] Average values for both plant-cover types.

[b] Not adjusted for concomitants, as none proved significant for this method in the initial study.

Table 2--Relative errors in measuring infiltration by four methods (Initial study)

Method	Mean squares for error	
	Unadjusted	Errors of estimate
Typ "F"	0.4516	0.2570
Rocky Mountain	0.7157	0.7157[a]
Modified North Fork	0.6416	0.3166
Square-foot	2.5760	1.0231

[a] The non-significant regression for this instrument accomplished no reduction in error, so that this figure is the unadjusted mean square.

tained by any given number of North Fork plots.

In examining this variability, both within and between infiltrometer-types, it is of fundamental interest to consider its causes. If all methods showed uniform variation between sites and no great discrepancy between averages, it might--perhaps erroneously--be assumed that all of the variance is due to variability of site, and none to instrumental errors. Then any indicated differences in average infiltration between instruments could be charged to variations in sampling the "universe" of infiltration in the soil involved. If this were the case, the differences between averages should not be significantly greater than the standard errors of the differences. Computation of the variance between instruments demonstrates, however, that the unadjusted average infiltration-rates for the several infiltrometers actually do differ significantly among themselves as shown by Tables 3 and 4. In these Tables, the significance of comparisons is shown by the ratios between the variances of comparisons and the "error" mean squares [14].

A certain, as yet poorly defined, amount of variability, then, must be charged to the individual instruments themselves, since they disagree even in sampling the same sites in the same general soil and cover-type. But what causes this variation; is it attributable to any factors inherent either in the instrument or in the environment, which can be subjected to control? Since several possible factors were measured in the field-work, perhaps this question can be partially answered by further analysis of results.

Table 3--Variance of infiltration as measured by four methods (Initial study)

Source of variation	Degrees of freedom	Mean squares
Total	119	1.3684
Between means of		
Infiltrometers	3	11.2389[a]
Sites	29	2.4312[a]
Interaction (error)	87	0.6738

[a] Highly significant ($p < 0.01$).

Accordingly, the next logical step was to segregate the individual influences of all controlled factors, and to calculate a new set of average infiltration-rates, adjusted to average values of all important associated factors.

In the initial study, this was accomplished by computing the multiple covariance of average infiltration by the four instruments on factors such as rainfall-intensity, soil-temperature, and the other measured concomitants. Of these, only rainfall-intensity was found to exert a significant influence; and soil-temperature, although not statistically significant, showed

Table 4--Variance and covariance of infiltration as measured by three instruments

Source of variation	Average infiltration[a]		Errors of estimate[b]	
	Degrees of freedom	Mean squares	Degrees of freedom	Mean squares
Total	107	0.4370	105	0.3147
Between means of				
Instruments	2	4.0018[c]	2	0.2900
Squares = 11 D/F				
Plant types	1	2.6499	1	0.4805
Sites within types	10	0.9721	10	0.7392
Rows within squares	24	0.4128	24	0.2522
Columns within squares	24	0.2717	24	0.2131
Interaction (instruments x squares; experimental error)	22	0.2446	20	0.2280
Internal error	24	0.1905	22	0.1636

[a] These mean squares express the relative amount of variation isolated by each factor, unadjusted for regression.

[b] Residual errors, after adjusting for the regression of infiltration on rainfall-intensity and soil-temperature. The regression-coefficient for rainfall $(b_{y1.2})$ is +0.3129; for soil-temperature $(b_{y2.1})$, it is +0.0076.

[c] Highly significant $(p < 0.01)$.

trends strong enough, and sufficiently consistent, so that it was considered worth while to include this factor in further analyses. Significant differences were again found between adjusted average infiltration-rates measured by the four infiltrometers (F = 13.01). Since regressions for individual instruments might also be expected to differ from one based on the average of all instruments, individual regressions were computed for each type of infiltrometer. As these were actually found to differ significantly from the average regression, the formulas obtained for each instrument were used in obtaining adjusted averages and errors of estimate (Tables 1 and 2).

A similar procedure was followed for the Latin-square study, with the additional feature that errors were further reduced by isolating variance due to plant-type, site, and variation within site, expressed by the variance between rows and columns within each Latin square (Table 4).

Considering first a comparison of the unadjusted and adjusted values for each method in both studies (Table 1), an exceedingly interesting fact becomes apparent. Obviously the concomitant factors must have exerted an appreciable influence on measured infiltration, as the new averages are in general rather different from the unadjusted means. This fact is important; it means that unadjusted averages should not be used in comparing different "populations" of infiltration, wherever any concomitant factors may be expected to exert a substantial influence.

As to differences between individual instruments, the adjusted average infiltration measured by the type-F plot is much higher than rates shown by the other three instruments; the square-foot plot shows relatively low rates; and the other two instruments agree very well with each other in both studies.

Another result of consequence is shown in the statistics of variance and covariance. In Table 2, for instance, isolation of the influences of rainfall-intensity and soil-temperatures--especially rainfall--is shown to have materially reduced the errors of the initial study. For the type-F plot, the "error" mean square was reduced by regression from 0.452 to 0.257; in other words, the precision of measurements by this method was almost doubled by placing concomitant factors under statistical control. It would be difficult to overstate the importance of this fact to field-workers in infiltration.

The profits involved in experimental and statistical control of variables are even more strongly presented by statistics of covariance for the Latin-square study (Table 4). In this analysis the data for all three types of apparatus were combined to demonstrate the isolation of a number of components of variation.

As a first step, the Latin-square data were analyzed by variance alone; the results are shown under "Average infiltration" in Table 4. From the total variation in the study (mean square = 0.4370, standard deviation = ±0.661 inch per hour) were extracted the variances due to instruments, plant-types, sites within types, rows and columns, the interaction between instruments and squares, and internal error. The experimental error (interaction) was much reduced by this means (to 0.2446), and the variation between instruments was shown to be significant. When regression alone was applied to the total variance, a material reduction in error was found (from 0.4370 to 0.3147)--even without extracting the discontinuous components of variation. Finally, as might be expected, a minimum figure for "error" was reached (0.2280, standard deviation = ±0.477 inch per hour) by a combination of variance and regression in an analysis of covariance.

Comparing adjusted infiltration-averages and statistics of variance and covariance for the Latin-square study, it will be seen that the use of regression has resulted in a great reduction in differences between instruments. For unadjusted averages, the variance between infiltrometers was significant and quite large (F = 16.36); when the means were adjusted for the influence of rain-intensity and soil-temperature, however, the differences became so much smaller that they were no longer significant (F = 1.27). This considerable reduction of error by the measurement and analysis of concomitant factors which influence measured rates of infiltration is of particular important to the design of infiltration-surveys. As shown by the data in Table 4, apparently most of the variance of unadjusted averages, for other factors as well as for instruments, was associated with variations in rainfall-intensity and soil-temperature. When measured rates of infiltration were adjusted to average values for these concomitant factors, most of the differences between instruments and plant-types were removed; and even the differences between sites and between rows and columns within squares were reduced. As a result, it is evident that the use of unadjusted averages may not only be accompanied by excessive computed errors, but may also indicate fictitious differences between cover-types or other factors which are the principal object of investigation.

Conclusions

By means of the group of studies which has been described and analyzed above, it is hoped that several useful facts have been demonstrated.

In the first place, infiltration-rates are characteristically variable. Judging from the relative magnitudes of measured variances of adjusted averages, the largest part of this variation occurs between sites in a single plant-type, and a smaller amount of variation may be charged to errors of instruments and technique.

As to the instruments themselves, any of the four infiltrometers can be expected to give only relative estimates of true infiltration. For some reason, perhaps associated with differences in distribution of applied water, the type-F instrument gave results higher than rates obtained with the three smaller instruments, which agreed relatively well among themselves. It is believed, however, that any of these four infiltrometers should give satisfactory estimates of relative infiltration-rates.

Perhaps the result of greatest consequence in this investigation is its demonstration of the reduction of experimental errors by the measurement and analysis of important concomitant factors. In this particular environment and of all the factors measured, rainfall-intensity appeared to exert the greatest influence upon infiltration. In other regions, other factors may be found important; in any case, it is imperative that measurements be taken of all significant variables, in every study of survey of infiltration. By a relatively small amount of additional field-work on each plot, the errors of individual measurements may be so greatly reduced that actually less plots may be needed for the whole survey than would otherwise be required; and the results will actually exhibit a materially greater degree of reliability.

Acknowledgment--Sincere acknowledgment is made for the aid of staff members of the Rocky Mountain Forest and Range Experiment Station, and for invaluable assistance in computations and analysis by Work Projects Administration Project No. 4294.

References

[1] E. L. Beutner and others, Sprinkled-plot runoff and infiltration-experiments on Arizona desert soils, Trans. Amer. Geophys. Union, pp. 550-558, 1940.
[2] Central States Forest Experiment Station, Infiltration studies, St. Francis Watershed, Missouri, mimeo., 1940.
[3] W. W. Horner and C. L. Lloyd, Infiltration-capacity values as determined from a study of an eighteen-month record at Edwardsville, Illinois, Trans. Amer. Geophys. Union, pp. 522-541, 1940.

[4] R. E. Horton, The role of infiltration in the hydrologic cycle, Trans. Amer. Geophys. Union, pp. 446-460, 1933.

[5] R. E. Horton, Surface runoff phenomena: Part I--Analysis of the hydrograph, Horton Hydrologic Laboratory, Pub. 101, 1935.

[6] R. E. Horton, Analysis of runoff-plot experiments with varying infiltration-capacity, Trans. Amer. Geophys. Union, pp. 693-711, 1939.

[7] R. E. Horton and R. Van Vliet, Determination of areal average infiltration from rainfall and runoff data, U. S. Dept. Agric., Office of Land Use Coordination and Flood Control, mimeo., 1940.

[8] G. W. Musgrave, The infiltration capacity of soils in relation to the control of surface runoff and erosion, J. Amer. Soc. Agron., v. 27, No. 9, pp. 336-345, 1935.

[9] G. W. Musgrave and G. R. Free, Some factors which modify the rate and total amount of infiltration of field soils, J. Amer. Soc. Agron., v. 28, No. 9, pp. 727-739, 1936.

[10] P. B. Rowe, The construction, operation, and use of the North Fork infiltrometer, U. S. Dept. Agric., Flood Control Coord. Com., Misc. Pub. 1, 1940.

[11] A. L. Sharp and H. N. Holtan, A graphical method of analysis of sprinkled-plot hydrographs, Trans. Amer. Geophys. Union, pp. 558-570, 1940.

[12] L. K. Sherman, The Horton method of determining infiltration-rates, Trans. Amer. Geophys. Union, pp. 312-316, 1936.

[13] L. K. Sherman, Deviation of infiltration-capacity from average loss-rates, Trans. Amer. Geophys. Union, pp. 541-550, 1940.

[14] G. W. Snedecor, Statistical methods (third edition), Iowa State College Press, 1940.

Rocky Mountain Forest and Range Experiment Station,
Fort Collins, Colorado

FACTORS INFLUENCING INFILTRATION-RATES INTO SOME CALIFORNIA SOILS

Martin R. Huberty and Arthur F. Pillsbury
(Presented by Arthur F. Pillsbury)

Introduction--In recent years considerable interest has been manifested in the study of factors influencing infiltration-rates of water into soils particularly by foresters and soil conservationists. The irrigationist is interested in this problem also, not alone from the point of view of the rate at which water enters an irrigated soil, but also in the matter of recharge of water-supplies by natural means or by water-spreading operations.

The data herein reported were collected in studies of infiltration-rates in an orange grove at Riverside, California, in potato fields near Wasco, California, and in plot-trials and laboratory studies at the University of California, Los Angeles. (We wish to express our appreciation to N. D. Hudson, Assistant Farm Advisor, Kern County, California, who was responsible for calling our attention to the problem of poor water-penetration in potato fields, and whose cooperation in all phases of the studies at Wasco made it possible to conduct the investigations; to Kurt Kecker who provided the land and water, and assisted in the field-studies; and to W. E. Picker for assistance in the studies at the Citrus Experiment Station, Riverside.)

The term infiltration-rate as used in this paper carries the same general meaning as defined by Free, Browning, and Musgrave [see 2 of "References" at end of paper], namely, the rate per unit of time at which water enters a soil when there is standing water on the soil-surface. Although the infiltration-rate curves were somewhat hyperbolic in shape, the rates reported herein are the average rates for a period starting after basins filled and water-surface was quiet, and concluded as soon as water no longer covered the entire ground. No general review of the literature dealing with infiltration will be made as this has been done by the authors referred to above.

Experimental data

Riverside investigations--During the summer of 1938 it was apparent that the infiltration of water into soil in an orange grove that was receiving large applications of water and fertilizer varied with the type of vertilizer used. The trees in this part of the orchard were single-tree basin-irrigated with an average depth of four inches of water every two weeks during the irrigating season. The irrigation-water has a total salt-content of between 300 and 400 ppm, and, of the cations, sodium represents on the average only about 35 per cent. Group A, which includes four trees, has received no fertilizer during the period 1938 to date; another series of four trees (Group B) has received ammonium sulfate at the following rates per basin (480

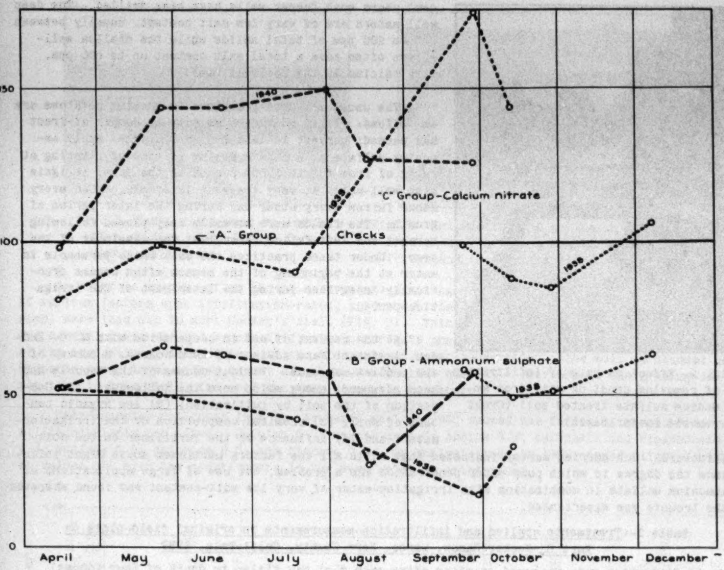


Fig. 1--Comparison of infiltration-rates in a single tree-basin irrigated orange orchard on Ramona sandy loam (Treatment A, not fertilized; B, ammonium sulfate spread in irrigation water; C, calcium nitrate fertilized)

square feet), 55 pounds during 1938, 24 pounds during 1939, and 17-1/2 pounds in 1940; Group C has received calcium nitrate as follows: 69 pounds during 1938, 31 pounds during 1939, and 23 pounds during 1940. The practice has been to apply the fertilizer to the basins in five seasonal applications, the fertilizer being spread following irrigation while there was still some water remaining on the surface of the soil. The soil is classified as Ramona sandy loam.

A comparison of average infiltration-rates for each set of four basins is shown in Figure 1. The average rates at which water entered the soil in the basins in Group A--plots receiving no fertilizer--are given a value of 100 and form the base for comparison with the results obtained in Groups B and C. This is a convenient method of plotting to show variations between treatments but does not show how the infiltration-rates of the check-plots may vary with time. This point is brought out later.

Applications of calcium nitrate tended to increase the rate of water-infiltration whereas ammonium sulfate had a retarding effect, especially during midsummer. That the retardation in rate of infiltration in the ammonium-sulfate-treated plots results mainly from a change in the character of the surface-soil is indicated by the conditions obtained when the crust of soil, about 1/4 inch in thickness, was removed. Figure 2 shows two basin-irrigated trees that had received equal amounts of ammonium sulfate and had comparable infiltration-rates. The crust of soil was removed from the farther basin and both basins were then irrigated. The Figure shows the conditions prevailing the next day, the water having disappeared from the scraped basin during the afternoon following irrigation. The effect of various chemicals upon the surface-layers of soil will be discussed under the next set of experiments.

Wasco studies--The Wasco Area, in the south part of San Joaquin Valley, California, produces a large quantity of early potatoes. Water for the district is obtained from wells of varying depths. At first the wells of this section were usually under 300 feet in depth, but in re-

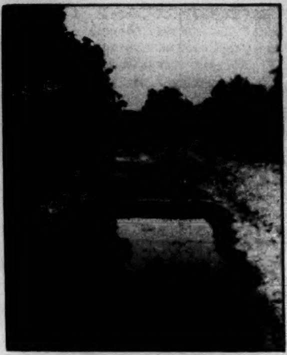


Fig. 2--Effect on rate of infiltration of removing crust of soil from ammonium sulfate treated soil (Crust removed in far basin)

cent years much deeper wells have been drilled. The deep well-waters are of very low salt content, usually between 100 to 200 ppm of total solids while the shallow well-waters often have a total salt content up to 600 ppm, with calcium as the dominant base.

The usual cultural practices in growing potatoes are as follows: Plant on ridges as soon as danger of frost has passed; harvest in late May, or in June; apply ammonium sulfate as a side dressing at time of planting at rates of from 400 to 1,000 pounds to the acre; irrigate with well-water at very frequent intervals, often every other furrow every other day during the later period of growth. The fields were normally deep-plowed following harvest and left fallow throughout the remainder of the year. Under these practices the soil while permeable to water at the beginning of the season often became practically impervious during the later part of the irrigation-period.

At the request of and in cooperation with N. D. Hudson, Assistant Farm Advisor of Kern County, a survey of the problem was made. Various causes of the trouble had been advanced, among which were the following: (1) Compaction of the soil by cultivation; (2) low organic content of soil; (3) chemical composition of the irrigation-water; and (4) influence of the fertilizer on the soil-structure. Our hurried survey indicated that while all the factors mentioned above might influence the degree to which poor water-penetration was a problem, the use of large applications of ammonium sulfate in combination with irrigation-water of very low salt-content was found wherever the trouble was experienced.

Table 1--Treatments applied and infiltration-measurements in original field-plots on Kurt H. Kecker Ranch, Wasco, Kern County, California, 1939

(Infiltration-rate measured starting after each plot had filled to depth of four inches)

Plot No.	Pre-treatment irrigation, inches per hour	Treatment applied September 11, 1939	2nd irrig. rate of change		3rd irrig. rate of change		4th irrig. rate of change		5th irrig. rate of change	
			Inches per hr	Per cent[c]	Inches per hr	Per cent[c]	Inches per hr	Per cent[c]	Inches per hr	Per cent[c]
1	1.61	5 lb $NaNO_3$	0.30	25	0.06	10	0.07	12	0.017	4
2	1.03	4 lb $(NH_4)_2SO_4$	0.35	44	0.08	21	0.32	82	0.040	14
3	1.57	Check	1.06	--	0.50	--	0.56	--	0.400	--
4	1.34	60 lb dry horse manure[b]	1.37	130	1.14	240	2.03	400	1.217	330
5	0.77	3 lb $NaNO_3$ + 2 lb $(NH_4)_2SO_4$	0.36	62	0.06	20	0.32	110	0.026	12
6	1.09	20 lb 93 per cent gypsum	1.24	150	0.79	190	0.78	190	0.571	190
7	1.22	20 lb $(NH_4)_2SO_4$	0.38	41	0.04	8	0.07	15	0.005	1
8	1.02	25 lb $NaNO_3$	0.11	14	0.01	3	0.01	3	0.002	1
9	1.63	20 lb 93 per cent gypsum	1.56	130	1.45	230	0.97	160	0.846	190
10	1.12	3 lb $NaNO_3$ + 2 lb $(NH_4)_2SO_4$	0.31	37	0.04	8	0.30	70	0.031	10
11	1.54	Check	1.33	--	0.71	--	0.59	--	0.461	--
12	1.18	Check	1.00	--	0.50	--	0.55	--	0.364	--
13	1.26[a]	120 lb dry horse manure[b]	2.36	250	2.75	560	5.13	1100	3.780	1100
14	1.06	13 lb 86.5 per cent gypsum	1.42	180	0.98	240	0.83	210	0.550	190
15	0.98	26 lb 86.5 per cent gypsum	1.87	250	1.14	300	1.12	300	0.905	330
16	1.76	Check	1.21	--	0.64	--	0.60	--	0.431	--

[a] Not obtained; assumed average found for all other plots.

[b] Turned under 2.5 inches on September 28, 1939; other plots not cultivated.

[c] Relative change in per cent = (average pre-treatment rate for check-plots times present rate times 100)/(present rate for check-plots times pre-treatment rate).

Fig. 3--Basin plots used in infiltration-studies, Kurt Kecker farm, Wasco, California

Fig. 5--Cultivating and partially removing clods from plots 7 and 8 on May 22, 1940, Plot 7 in foreground (See Tables 1 and 3)

In order to obtain, prior to the next potato-planting season, information on the influence of various factors upon infiltration-rates, a series of level basin-plots (10 feet by 15 feet each) were laid out in Kurt Kecker's field (Fig. 3). This field had been planted to potatoes for several years and had become difficult to irrigate properly during the middle and late part of the irrigation-season because of the slow rate of water-penetration. The soil is classed as Hesperia sandy loam, a deep recent alluvium of high lime-content. Previous to the growing of potatoes in this field, the soil was very permeable to water.

Water-samples collected from Mr. Kecker's well in 1937 showed the following composition in milliequivalents per liter: Calcium 0.7; magnesium 0.7; sodium 0.7; carbonate and bicarbonate 1.4; sulfate 0.2; chloride 0.3; and nitrate 0.1. An analysis made in 1939 showed slightly higher values but with the constituents in the same relative proportions.

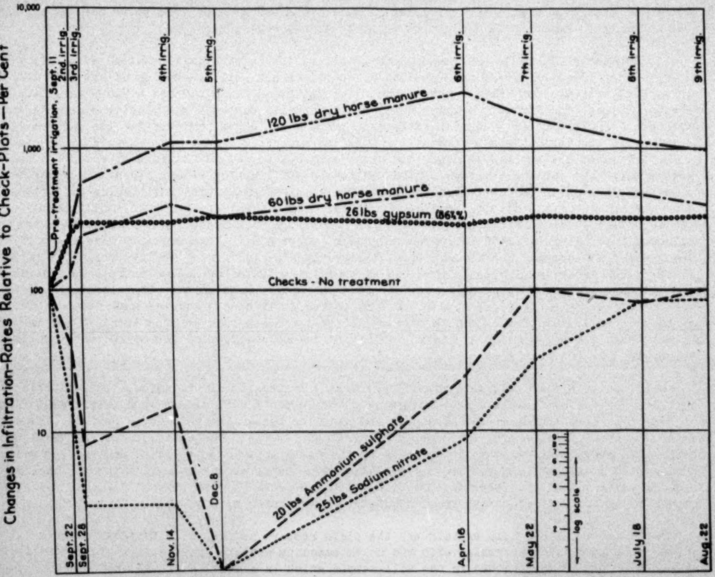


Fig. 4--Typical infiltration-rates, Kurt Kecker farm, Wasco, California

Table 2--Conductance of irrigation waters and base exchange in surface samples of Hesperia sandy loam soil near Wasco, California

Soil-samples		Conductance of irrigation-water K 10^5 at 25°C	Milliequivalents per 100 grams of soil						
			NH_4 absorbed	In ammonium extract					Difference [(3)-(8)]
No.	Description (1)	(2)	(3)	Ca (4)	Mg (5)	Na (6)	K (7)	Total bases (8)	(9)
1	Virgin	----	7.72	9.50	----	1.95	----	----	----
2	Poor penetration	16.7	9.16	6.95	----	2.17	----	----	----
3	Good penetration	75.7	8.70	10.15	----	2.14	----	----	----
4	Plot 8 ($NaNo_3$)	16.7	13.1	6.86	0.93	4.67	0.71	13.17	0.0
5	Plot 7 [$(NH_4)_2SO_4$)]	16.7	12.1	6.46	0.93	0.41	0.43	8.23	+3.87
6	Plot 13 (manure)	16.7	10.3	10.58	1.10	0.28	1.49	13.45	-3.17
7	Plot 15 (gypsum)	16.7	12.5	39.40	0.83	0.31	0.64	41.2	-28.7

Note: Samples 1 to 3 were preliminary, collected in summer 1939: (1) From edge of roadway; (2) clod from plowed potato field wherein water-penetration was poor; (3) from potato field irrigated with high calcium water, no trouble. Samples 4 to 7 collected May 22, 1940, from Kurt H. Kecker Ranch plots.

A stake was driven vertically into each of the 16 basins. On a side of each stake was driven a nail four inches above the ground-surface of the basin, this being the depth to which the basin was filled with water. The top of each stake was a datum from which changes of 0.001 foot in depth to water surface could be measured with a hook-gage.

On September 11, 1939, water was added to all basins and the infiltration-rates were measured. After these rates had been obtained, fertilizer and soil-amendments of the kind and in the amounts indicated in Table 1 were added. The amounts applied covered a wider range than normal applications. Through a false sale, sodium nitrate was used where calcium nitrate was intended. Figure 4 shows infiltration-rates expressed in inches per hour for the various treatments during the period from September 11, 1939, to August 22, 1940. The curve for the check-plots represents the average for the four non-treated plots and is the gage by which one can judge whether the various treatments have influenced infiltration-rates. Those lines markedly below the check-curve indicate that the treatment given had retarded infiltration while those above the check-curve indicate increases in rates. Organic matter increased infiltration to such an extent it was not feasible to plot the results on this scale. Ammonium sulfate and sodium nitrate retarded infiltration while gypsum increased it. Measurements made in April, 1940, showed an increase in rate for these latter-named plots. Prior to the irrigation of May 22, the plots receiving large applications of ammonium sulfate and sodium nitrate were divided longitudinally into two equal parts and one side was spaded with part of the clods being removed. A dense brick-like surface layer of about four inches in thickness covered both sets of plots, as shown in Figure 5. The marked improvement in infiltration-rate between April 16 and May 22 may have partially resulted from the rupturing and removal of some of the soil-crust, and from seepage through the new levee.

Noticeable in the field were the differences in dispersion of the soil-particles during irrigation. In the sodium-nitrate and ammonium-sulphate plots soil almost immediately went into suspension so that the water became muddy. No definite top of the soil could be felt, the consistency gradually increasing for a depth of over four inches. The water-stable aggregation of the soil in other plots was obvious because of the clean water and the continuously firm ground-surface. This was particularly so in the plots having received the organic matter. These findings are in agreement with the findings of Demolon and Henin [1], and Myers [6], that colloidal organic matter is very effective in forming stable aggregates with sand.

The data in Table 2 help explain why the plots respond as they do. Various 100-gram surface-soil samples were treated with 500 cc of ammonium acetate and the filtrate was collected. The amount of ammonium retained in the soil-sample which is a measure of the base-exchange capac-

Table 3--Further treatments and subsequent infiltration-rate measurements in original field-plots on Kurt H. Kecker Ranch, Wasco, California, 1940 (same plots and data computed as in Table 1)

Plot No.	Further treatment applied December 9, 1939	6th irrig. rate of change		7th irrig. rate of change		8th irrig. rate of change		9th irrig. rate of change	
		Inches per hr	Per cent	Inches per hr	Per cent	Inches per hr	Per cent	Inches per hr	Per cent
1	3 lb sulphur (85 per cent)	0.132	34	0.238	70	0.372	91	0.360	81
2	30 lb lime [85 per cent $Ca(OH)_2$ + 15 per cent $CaCO_3$][b]	0.276	110	0.297	140	0.324	120	0.348	120
3	No treatment (check)	0.360	---	0.319	---	0.384	---	0.420	---
4	No further treatment	1.580	500	1.440	510	1.610	470	1.500	400
5	No further treatment	0.252	140	0.218	140	0.312	160	0.324	150
6	1 lb barley seed[a] + 5 lb $Ca(NO_3)_2$[b]	1.670	640	1.450	630	1.540	550	1.370	450
7N	Cultivated 4-inch depth; part of clods removed[c]	0.072	25	0.398	150	0.372	120	0.408	120
7S	Surface undisturbed[c]	-----	---	0.257	100	0.252	81	0.348	100
8N	Surface undisturbed[c]	0.022	9	0.068	32	0.240	93	0.240	85
8S	Cultivated 4-inch depth; few of clods removed[c]	-----	---	0.082	38	0.252	97	0.480	170
9	No further treatment	0.636	160	0.632	180	0.600	140	0.768	170
10	1 lb barley seed[d]	0.264	100	8.440	3600	6.140	2200	5.090	1600
11	3 lb sulphur (85 per cent)	0.744	200	0.567	180	0.552	140	0.588	140
12	30 lb lime [85 per cent $Ca(OH)_2$ + 15 per cent $CaCO_3$][b]	0.684	240	0.452	180	0.432	140	0.444	140
13	No further treatment	7.450	2500	4.240	1600	3.520	1100	3.380	970
14	No further treatment	0.648	260	0.545	240	0.540	200	0.576	200
15	No further treatment	0.672	290	0.690	330	0.792	320	0.900	330
16	5 lb $NaNO_3$	0.067	16	0.098	26	0.240	54	0.264	54

[a] Barley pulled up by hand when 2 to 3 inches high. [b] Applied on January 18, 1940. [c] Plots 7 and 8 divided in half, and treatments above mentioned were performed just prior to irrigation on May 22, 1940. [d] Barley grew to maturity and was hoed under some time between April 16 and May 22, 1940.

ity of the soil, was determined. The filtrate was analyzed for calcium, magnesium, sodium, and potassium. Soils 1, 3, 6, and 7 have a higher calcium-content than the soils from the sodium-nitrate and ammonium-sulphate plots. It has long been recognized that soils high in calcium and magnesium, or both, tend to be more permeable than high-sodium soils.

Figure 6 is a logarithmic presentation of the data shown in Figure 4, together with relative rates for plots receiving manure. The average rates for the four check-plots have a value of 100 on the logarithmic scale.

Following the fifth irrigation of the plots on December 8, 1939, certain variations in the plot-treatments were made (see Table 3). Results obtained for these plots are shown in Figure 7. Thirty pounds of calcium carbonate applied to a check-plot tended to increase infiltration-rates slightly, while three pounds of sodium nitrate added to a check-plot decreased infiltration-rates materially. Application of calcium carbonate to a plot previously treated with ammonium sulfate resulted in an increase in infiltration-rate. Marked improvement occurred in a previously impervious plot when barley plants were grown and turned under. While the number of plots here represented are very limited, the results are in agreement with the general results of all experiments.

Table 4 gives for various plots pH-values at the field-moisture contents shown and pH-values of 1:5 distilled-water suspensions. The determinations were made seven months after the last irrigation and after a winter's rainfall of about ten inches. Values for soil from ammonium-sulfate and sulphur treatments are relatively low. At the 1:5 soil-water ratio, the samples from plots receiving manure or lime had the highest pH-values, but were not markedly above the sodium-nitrate treatments.

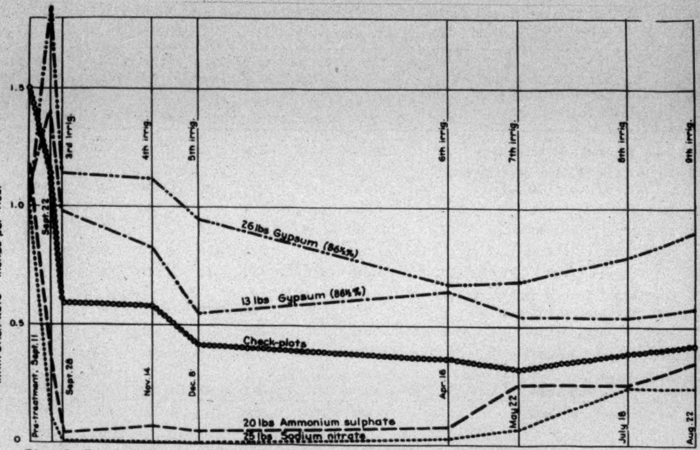


Fig. 6--Comparison, on logarithmic scale, of infiltration-rates in basins treated with various materials, Kurt Kecker's farm, Wasco, California

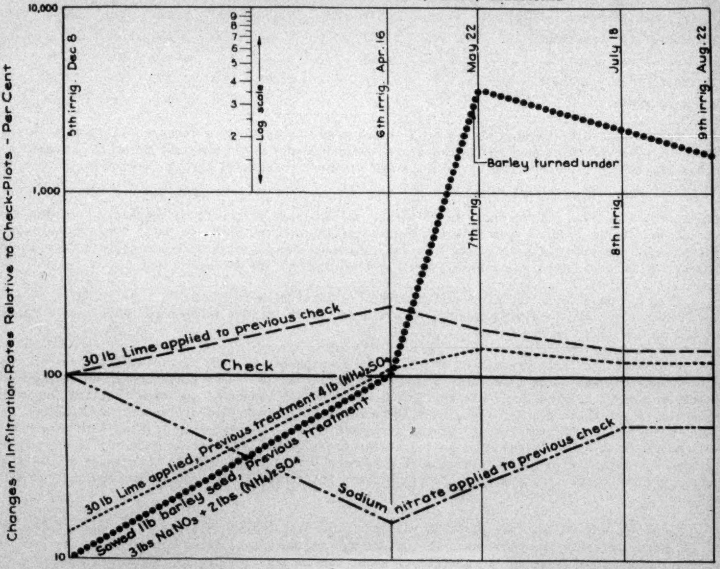


Fig. 7--Comparison, on logarithmic scale, of changes in infiltration-rates resulting from secondary treatments, Kurt Kecker's farm, Wasco, California

Table 4--Results of pH-determinations and moisture-content of soils of Kurt H. Kecker Ranch plots, Wasco, California; determinations made March 21, 1941, with Beckman glass-electrode (soil-moisture was approximately at field-capacity)

Plot No.	pH at field-moisture			Moisture-percentage				pH with 1:5 soil-water ratio			
	0 to 0.1-ft depth	0 to 1-ft depth	1 to 2-ft depth	0 to 0.1-ft depth	0 to 1-ft depth	1 to 2-ft depth	2 to 3-ft depth	0 to 0.1-ft depth	0 to 1-ft depth	1 to 2-ft depth	2 to 3-ft depth
3	---	6.1	6.8	---	9.4	9.0	10.5	---	7.38	7.99	8.90
4	---	6.0	6.6	---	10.1	9.2	10.9	---	8.23	8.70	8.86
5	---	6.3	6.7	---	9.5	10.0	10.9	---	6.94	8.50	8.92
7S	5.3	5.4	5.9	---	9.4	8.8	8.6	---	6.23	7.80	8.52
8N	---	6.5	6.4	---	10.7	8.2	8.0	---	7.72	8.13	8.27
10	---	6.7	6.6	---	9.1	8.5	8.6	---	7.19	8.65	8.89
11	---	5.8	5.9	---	9.5	8.8	9.0	---	6.54	8.25	8.73
12	7.1	6.9	6.9	10.0	9.0	9.4	---	7.71	8.78	8.85	---
13	---	6.4	6.6	---	9.2	9.0	9.2	---	7.80	8.45	8.69
14	6.5	6.1	6.8	8.4	8.9	7.9	9.2	7.49	7.21	8.26	8.86
15	---	6.4	6.8	---	8.2	8.2	8.2	---	7.35	8.61	8.77
16	6.4	6.4	---	---	10.9	---	---	7.40	7.74	---	---

Table 5--Treatments applied and results of infiltration-rate measurements in "A"-series field-plots on Kurt H. Kecker Ranch, Wasco, California, 1940; methods and computations same as for original plots (second irrigation used as pre-treatment irrigation

Plots No.	Pre-treatment irrigations		Treatments applied after irrigation May 1, 1940	3rd irrig. rate of change		4th irrig. rate of change		5th irrig. rate of change	
	1st March 15, 1940	2nd May 1, 1940		Inches per hr	Per cent	Inches per hr	Per cent	Inches per hr	Per cent
1A	3.85	1.56	Check	1.38	---	1.63	---	1.49	---
2A	2.70	1.17	Uramon, 350 lb per acre	1.11	104	1.31	109	1.24	106
3A	4.04	1.51	Cotton hulls, 8000 lb per acre	2.88	208	4.04	261	3.08	204
4A	2.43	1.42	Compost, 8000 lb per acre	3.20	246	2.69	185	2.12	149
5A	3.76	1.89	"Cactus juice,"[a] 18.2 gal per acre	1.36	79	1.43	74	1.25	66
6A	3.11	1.46	$Ca(NO_3)_2$, 850 lb per acre	1.22	91	1.37	92	1.48	101
7A	3.34	1.70	"Calcium polysulfide + cactus juice,"[a] 18.2 gal per acre	1.08	69	0.78	45	1.31	77
8A	2.99	1.27	Check	1.35	---	1.49	---	1.51	---
9A	5.06	2.05	$(NH_4)_2SO_4$, 650 lb per acre	1.09	58	1.31	62	1.32	64
10A	4.95	1.72	Alfalfa meal, 8000 lb per acre	5.06	321	3.59	204	4.08	237
11A	3.17	1.64	Check	1.38	---	1.56	---	1.54	---
12A	4.48	1.69	Same as 5A	1.48	96	1.55	90	1.48	88
13A	2.54	1.61	Same as 2A	1.26	85	1.44	87	1.43	89
14A	4.36	1.60	Same as 9A	1.45	99	1.66	101	1.63	102
15A	2.86	1.26	Same as 4A	2.69	233	2.53	196	2.20	175
16A	3.99	1.66	Same as 3A	3.76	247	3.52	207	3.22	194
17A	2.14	1.02	Same as 6A	1.09	117	1.21	116	1.14	112
18A	2.12	1.10	Same as 7A	1.19	118	1.37	121	1.36	124
19A	1.71	0.83	Same as 10A	2.26	297	3.25	382	2.44	294
20A	1.11	0.87	Check	0.78	---	0.79	---	0.79	---

[a] Commercial "soil-amendments."

In April, 1940, 20 additional plots, designated A-plots, were laid out adjacent to the old series. During the summer of 1939 a cover-crop of barley and mustard had been grown and turned under, and in the early spring of 1940, 86 per cent gypsum at the rate of seven tons to the acre

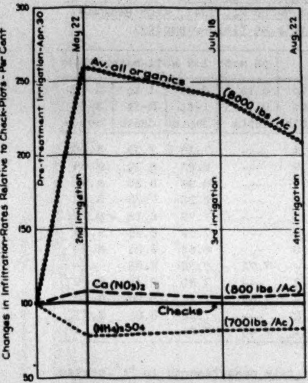


Fig. 8--Comparison of infiltration-rates on "A" plots receiving treatments of organic material, ammonium sulfate, or gypsum, Kecker farm, Wasco, California

had been applied to the land on which the new plots were placed. Table 5 indicates the treatments applied, and Figure 8 illustrates the results obtained with organic material, calcium nitrate, and ammonium sulfate. Even in this soil, which had received a relatively large application of gypsum, commercial rates of application of ammonium sulfate somewhat depressed infiltration-rates.

Other investigations--On the campus of the University of California, Los Angeles, 32 wood-walled basins, three feet by three feet, have been constructed in a Yolo loam soil. Measurements to determine infiltration-rates under various conditions have begun.

Laboratory studies are also under way on the effect of soil-condition and method of application of water on infiltration-rates. This investigation is also concerned with the decrease in infiltration-rates which often follow with adoption of the sprinkler-method of irrigation, and is particularly noticeable where the coarse-drop, low-pressure, sprinklers are used on bare soil.

Summary

In basin-irrigated plots in an orange grove on Ramona sandy loam soil, surface-applications of about double commercial rates of ammonium sulfate and calcium nitrate to the soil-surface following irrigation materially influenced infiltration-rates, the former depressed the rates, the latter increased them.

It is shown that the retarding effect is confined in the main to the surface-soil.

Studies made in cooperation with N. D. Hudson, Assistant Farm Advisor of Kern County, California, showed that poor penetration of water in potato fields on Hesperia sandy loam soil resulted from the use of large applications of ammonium sulfate in combination with low calcium-content irrigation-water. Applications of organic matter and/or gypsum to fields that had been affected adversely by ammonium sulfate resulted in marked improvements in infiltration-rates.

References

[1] A. Demolon and S. Henin, Recherches sur la structure des limone et la synthese des aggregates, Soil Res. 3, pp. 1-9, 1932.
[2] G. R. Free, G. M. Browning, and G. W. Musgrave, Relative infiltration and related characteristics of certain soils, U. S. Dept. Agric. Tech. Bull. 792, pp. 1-51, 1940.
[3] N. D. Hudson, Progress-report, Wasco water penetration tests, Univ. Calif. Agric. Ext. Serv., mimeo., 1940.
[4] N. D. Hudson, Improved water penetration in Kern tests, Pac. Rural Press, v. 139, No. 8, pp. 298-299, 1940.
[5] N. D. Hudson, Wasco water penetration test, Univ. Calif. Agric. Ext. Serv., mimeo., 1940.
[6] H. E. Myers, Physico-chemical reactions between organic and inorganic soil colloids, as related to aggregate formation, Soil Sci., v. 44, pp. 331-357, 1937.

University of California at Los Angeles,
Los Angeles, California

DISCUSSION

N. E. EDLEFSEN (University of California, Davis, California)--A knowledge of infiltration-rates and the factors influencing them is of prime importance in soil- and water-conservation, but is of special interest in irrigation-regions since any rational irrigation-practice must necessarily take into account, not only the infiltration-rates at a particular time, but the probable influence of present cultural practices on future infiltration-rates. It is not an

Table 1--Asymptotic rate of penetration in centimeters per minute for each plot

Date	Plot									
	A	B	C	D	E	F	G	H	I	J
July 1940	.10	.10	.12	.15	.11	.10	.05	.10	.05	.10
Oct. 1940	.10	.09	.09	.07	.08	.08	.04	.05	.04	.04
Dec. 1941	.19	.20	.20	.19	.18	.22	.20	.47	.41	.37
and	.13	.12	.11	.07	.08	.10	.11	.18	.19	.19
Jan. 1941	.10	.13	.13	.10	.09	.12	.13	.19	.17	.18

uncommon experience in irrigated regions to find a farmer wetting the surface of his field and assuming that he had given it sufficient irrigation, whereas the soil may be wet only to a shallow depth. Data on this subject, under field-conditions, are scarce. Those furnished in the paper by Huberty and Pillsbury are a valuable addition.

In discussing this paper, I should like, in the beginning, to point out what seem to be pertinent facts with which one has to contend in dealing with any problem wherein rates of penetration of water into soils is to be measured.

When water is first applied to a field-plot, the rate of infiltration is comparatively rapid and gradually decreases with time to an asymptotic or approximately steady value which seems to be more or less characteristic of the plot at that particular time. Hence it seems difficult to choose any particular point on the rate-of-penetration curve as a function of time as having any particular meaning other than the asymptotic or steady value. The difficulty with using this value, however, is that it is only reached after a considerable time. The time required to reach the steady rate is usually longer than required for an ordinary application of irrigation-water to penetrate into the soil. Hence, from a practical viewpoint, this value has, in many cases, perhaps questionable significance. The best that the experimenter can do, when ordinary applications of irrigation-water are applied, is to measure an average rate of penetration. This is what Huberty and Pillsbury have done in their paper.

A second difficulty with which one has to contend in such measurements is that even the asymptotic value of a given plot of ground may change by several hundred per cent during a year with no apparent change in the surface-conditions of the soil, and no cultivation. A series of ten plots at Davis, California, for example, have been laid out and no differential treatment has been made to date. We are at first trying to find what fluctuations in penetration-rates on a given plot might be expected with no apparent change in the cultivation or treatment of the plot. The measurements made during the last season on these ten plots will illustrate the results. These are shown in Table 1. Volunteer weeds containing a large percentage of barley grew on the plots in the spring. Before this growth went to seed, it was cut and taken off the plots. Irrigations of about a foot in depth were applied on the approximate months shown in Table 1. Each series of irrigations occupied several days. As can be seen, some of the plots showed a marked increase in the rate of penetration of water during December and January over what they showed in July and October. During the first irrigation in December all of the plots showed a distinct increase over the treatments in the summer. The last two series of treatments during the winter are lower than the first series. This is usually found to be the case where heavy irrigations are applied at short intervals. It will be noted that some of the rates during the winter are several hundred per cent more than what they are during the summer. If it were a matter of viscosity of the water, one might expect the rates to be smaller in the winter than in the summer. Hence this does not seem to account for the result. Another factor which might have an important bearing is that roots produced by the crop in the spring might have decayed sufficiently during the summer to open up channels of sufficient magnitude to account for the increase in rate of penetration. This work, of course, is being continued and the Table is presented here only to indicate the degree of variability that one might expect under field-conditions.

In spite of the difficulties pointed out above, the results of Huberty and Pillsbury seem to be so consistent and the differences are of such magnitude that definite conclusions can be drawn. Their results indicate, it seems beyond question, that calcium fertilizers as well as organic fertilizers tended to increase the rate of penetration of water under the conditions where they worked; whereas fertilizers composed largely of ammonium and sodium salts tended to depress the rate of penetration of irrigation-water. This is, of course, what one might expect from a consideration of base-exchange phenomena, although explanation of the effect of organic fertilizer is perhaps not so well understood. In this connection, it is well worth while pointing out that the effect of inorganic base-exchange was discussed in the report of the Committee on Physics of Soil-Moisture, 1935-36, "Physical properties of soils as affected by the degree of cation-saturation," while the effects of organic fertilizers were discussed in the report of the Committee on Physics of Soil-Moisture, 1937-38, "Effect of organic matter on the infiltration of water into soils." A point of particular interest is that their results further indicate that the phenomenon is largely on the surface of the soil where it is probable that some mechanical manipulation is experienced by the soil during actual application of water. It would be interesting to know what effect the mechanical manipulation of the soil, in connection with the application of the fertilizers, has on the infiltration-rates.

ROBERT E. HORTON (Voorheesville, New York)--The authors of the paper have presented the results of an excellent research on the effect of fertilizers and soluble salts on the rate of absorption of irrigation-water by the soil. The title of the paper is "Factors influencing infiltration-rates in some California soils." Here, as in several preceding papers, the term "infiltration-rates" has been used where "infiltration-capacity was intended. In case of infiltration of rainfall, infiltration-capacity has been defined by the writer [Trans. Amer. Geophys. Union, p. 446, 1935] as "the maximum rate at which the soil when in a given condition can absorb rain as it falls."

Consider the case of a given soil with and without fertilizer. If the infiltration-capacity is f_1 without, and f_2 with, fertilizer, and the rain-intensity is less than either f_1 or f_2, the rain will be absorbed as fast as it falls, or the infiltration-rate will equal the rain-intensity, and the presence of salts or fertilizer in the soil will have no effect whatever on the infiltration-rate, although it may have an important effect on the infiltration-capacity. It is evident that the use of the term "infiltration-rates" where "infiltration-capacity" is intended may lead to serious confusion and inaccuracy of statement.

Quantitative hydrology is a relatively new and rapidly growing science. It is inevitable that difficulties in precise definition of terms should arise. As a science changes from a qualitative to a quantitative basis, general, descriptive, and qualitative terms must be replaced and give way to definite, specific terms. The paper by Sherman [pp. 666-777] serves for illustration. This reads: "Application of the infiltration-theory to engineering practice." The expression "recession-curve of infiltration-capacity" might well be replaced by the simple words "infiltration-capacity curve." It is true that an infiltration-capacity curve, as pointed out by the writer [Trans. Amer. Geophys. Union, p. 697, 1939] is in general a decreasing function of the time. Any curve--and there are many--which is a decreasing function of the independent variable or variables by which it is governed might equally well be called a "recession-curve."

Again, the expression "loss-rates" is used in a manner which makes it essentially synonomous with "infiltration-capacity" although as there used, the loss-rates includes, in some cases, interception-rate. In other cases there is no interception. If interception occurs it may very properly be included with infiltration if so specified.

The argument of the author of the paper in favor of using the term "loss-rate" for "infiltration-capacity" is that it is a loss of runoff. It is worth while to examine the accuracy of this statement. Runoff in general consists of two parts, namely, surface-runoff and ground-water flow. Infiltration is the source of ground-water flow. Hence the portion of infiltration which goes to supply ground-water flow is not a loss of runoff.

In a recent Government publication [Influences of vegetation and watershed treatments on runoff, silting, and stream-flow, U. S. Dept. Agric. Misc. Pub. 397, p. 29], one finds "surface-runoff" referred to as "water-loss." Unquestionably infiltration reduces surface-runoff; hence surface-runoff may be considered as a loss of infiltration, but this is not necessarily a water-loss. Now if infiltration is a loss and surface-runoff is a loss, then since (infiltration + surface-runoff = ground-rainfall), all rainfall which reaches the ground on any drainage-basin is lost. The word "loss" should not be applied either to surface-runoff or to infiltration, since neither one is a loss in the generally accepted meaning of the term "water-losses."

The expression "water-losses" is generally applied in English-speaking countries all over the world to the loss of water from a drainage-basin through evaporative processes, and to nothing else, and should be so and only so applied. [See U. S. Geol. Surv., W.-S. Paper 846, 1940.]

The writer hopes that these comments may be accepted as constructive suggestions, applicable to other papers as well as those cited.

L. K. SHERMAN (Chicago, Illinois)--Referring to Dr. Horton's remarks on the use of the terms "loss-rates" and "infiltration-capacity", it is frequently desirable to use the terms "loss-rate", "infiltration-rate", or "average loss-rates."

The volume of water entering the ground, during rainfall-rates at less than infiltration-capacity, is frequently greater than the volume furnished at infiltration-capacity. The term "infiltration-rate" is needed to discuss this phenomenon.

The symbol f_a is properly called "average areal infiltration-capacity" when the derivation of this f_a excludes the water used up in initial wetting of the soil, vegetation, or filling pockets. The term f_{av} is properly called "average loss-rate" when it is derived by the common procedure of equating the volume of rain-excess with the volume of observed runoff. Therefore, I shall continue to use the term "average loss-rate" or f_{av} in the latter case.

Before the term "infiltration-capacity" was invented, all engineers knew that "loss" meant the difference between total rain and total runoff.

CONSIDERATIONS ON AN INDEX TO MEASURE EFFECTIVE RAINFALL

José Garcia Montes

(Presented by title)

Some years ago I tried to find some summary expression for the combined effect on plant-yield of the different aspects of rain.

Usually the value of rainfall is judged from the total amount fallen during a cycle of plant-growth or at most, during certain periods which are known to be critical in the water-requirements.

Three different aspects of rain were to be considered: (a) Intensity; (b) quantity; and (c) opportunity.

The intensity may, of course, be referred to quantity, as the sole difference between the two refers only to the period of time being considered. Automatic rainfall-registers have been used for a long time to measure the intensity; they are, however, high-priced and also require much care in their handling. Moreover, in agricultural practice we are interested in the intensity of the rainfall in so far as it bears on the amount which penetrates the soils. If we have the data of an automatic rainfall-register we cannot determine from this information what portion of the total would have penetrated a certain soil. There is not, as far as I know, any approved method of calculating the penetration of the rainfall from a knowledge of its intensity alone, as the penetration depends also on other factors equally important.

If we cannot arrive at the penetration by direct calculation from the best of rainfall-intensity data alone, it seems quite useless to measure the intensity by a refined apparatus. It is known that the penetration depends on: (1) Intensity of rainfall; (2) the intrinsic capacity of the soil to absorb and transmit water; and (3) the physical state of the soil at the moment rainfall occurs. We take no account of vegetation, figuring on tilled soils. Rainfall-interception by growing crops may be taken into account by dropping all precipitation below a certain amount and discounting varying amounts from the higher figures.

Item (3) depends, of course, on the meteorological factors known to affect the capacity of a certain soil to absorb water, but even if we measure all these factors we still do not know how to relate them to the penetration. It stands to reason that the best thing is to allow the meteorological factors of the place of observation, whatever they are, to act on a standard soil and let this tell us how much water it will absorb at any moment from rainfall, under any intensity. The soil to be used in the apparatus I called an escurrimetro (or a modified lysimeter) may be as stated, a soil which has been standardized, or we may use the same soil where the crop or crops are being grown. When rainfall occurs under any intensity, we take as net or active, only that part of it which penetrates the soil of the apparatus. This is to be obtained by subtracting from the total, as measured in a standard rain-gage, the amount collected in the runoff-can of the escurrimetro.

It is realized that the runoff under field-conditions will not be the same as that measured in the apparatus principally because of variations in the soils. Differences in slope do not seem to affect the runoff as they are not large in agricultural practice. No very close approximation can be expected for the total rainfall corrected by escurrimetro-data and that which actually penetrates the soil in surrounding farms even if we apply some correction based on the water-holding capacity of the standard soil and that corresponding to a mean figure applying to the farming lands; but it is emphatically believed that the total rainfall corrected by the data of the escurrimetro will be much more significant in agricultural practice than the uncorrected total measured in the standard rain-gage. So much for the apparatus, which is nothing more than a small circular runoff-plot one foot in diameter and two feet deep, with an overflow- and a drainage-pipe leading to separate collecting cans, which serves a different purpose than that of studying the runoff itself.

If the total rainfall collected during the period from seed to harvest of a certain crop is discounted by the total amount during the same period which is collected in the overflow-can of the escurrimetro, we should have a better basis for judging the value of the rainfall to a crop.

We must go further, however, as the total amount, corrected for intensity may have actually occurred in concentrated storms during one-half of the time, leaving long droughty periods in the other half. It may, on the contrary, be evenly distributed, or better than this, distributed according to the requirements of the crop. Any form of distribution may well be spoken of as the opportunity of a certain total amount, or rather of its components. We are in need, therefore, of some form of expression which takes into account the manner in which the rainfall is distributed. An index of the form of a standard deviation will not answer the purpose as it only measures the abstract distribution or variation from a certain norm, not taking into account the sequence. A given corrected total may be very evenly distributed in time, and still not suit the water-requirements of a crop. As a rule the water-requirements of crops do not follow straight lines but approximate parabolas.

The degree of agreement of a set of figures corresponding to observed rainfall in any element of time with the corresponding water-requirements for the same time-periods of a given crop, be they represented by parabolas or any other form of distribution, can best be represented by the well-known statistical index called "standard error of estimate." We may thus finally arrive at an index which will take care of the three aspects of the rain as stated hereinbefore. We first proceed to work out what are the water-requirements of the crop. Different crops may differ considerably in this respect; hence, any computed index is significant only to the crop from whose water-requirements it was obtained. A given rainfall-regime will give different values of the index according to the crop whose water-requirements are used as the basis of comparison. The water-requirements of different agricultural crops for any convenient time-period in a standard soil are to be worked out by soil specialists and agricultural technicians from controlled experiments. For the sake of brevity we may refer to the standard water-requirements of a certain crop simply as the standard for the crop.

Illustrative example--From data of Maxwell and Crawley, I give in Table 1 the approximate standard for a sugar-cane crop sown October 1 in Matanzas clay-soil for a mean temperature of 75° F, divided in 21 periods. The total time from seed to harvest was 450 days. Each period corresponds therefore to 21.4 days. The figures in column (3) are the water-requirements corresponding to each of the 21 elementary periods.

If instead of sugar-cane we consider corn, for instance, with a total time from seed to harvest of say 120 days, each time-element will represent 5.7 days. We may, of course, divide the total time in any other convenient time-units. The important point to bear in mind is that the number of days included in each period should not be in excess of the significance of drought on the given crop. If the time-element be too large it is conceivable that the rainfall which is given as totals for each time-element may have occurred in one of the several days included in the time-period, allowing for many consecutive days with no rain, which fact may prove limiting or at least damaging to the crop and we cannot take account of it. It is believed that 21 terms fairly approximate a division of time which will suit any crop. From this division it apparently follows that sugar-cane can go without water for 20 days as easily as a corn crop can for 4.7 days; but this is not a necessary consequence as it is much more probable for the total corresponding to a 5.7-day period to occur in one single day than given for a 21-day period to so occur. A standard, it should be stressed, strictly applies to a certain crop-variety or even strain growing in a certain soil, under known temperature, humidity, etc., if these meteorological factors are taken into account. It is believed, however, that variations in these factors will affect the yield of crop in a limited way and they are best taken into account by limiting the application or use of a standard to crops sown in approximately a fixed day of the month. By so doing we do away with the systematic variations from month to month, especially in temperature.

Table 1--Approximate standard water-requirements for a sugar-cane crop

Time-period (1)	As a per cent of total-duration of crop (2)	Water-requirements, inches (3)	Observed rainfall, inches (4)	Differences + (5)	Differences - (5)	Differences squared (6)
1	0	0.93	1.50	0.57	....	0.325
2	5	0.28	0.00	....	0.28	0.078
3	10	0.43	0.10	....	0.33	0.108
4	15	1.43	2.50	1.07	....	1.145
5	20	1.94	0.40	....	1.54	2.372
6	25	2.87	0.40	....	2.47	6.100
7	30	3.37	1.20	....	2.17	4.709
8	35	3.37	2.00	....	1.37	1.877
9	40	3.85	8.00	4.15	....	17.222
10	45	4.59	6.00	1.41	....	19.881
11	50	5.23	0.50	....	4.73	22.373
12	55	6.80	1.50	....	5.30	28.090
13	60	6.80	1.50	....	5.30	28.090
14	65	6.45	14.00	7.55	....	57.002
15	70	6.20	12.00	5.80	....	33.640
16	75	5.73	4.00	....	1.73	29.929
17	80	4.73	0.00	....	4.73	22.373
18	85	3.70	0.00	....	3.70	13.690
19	90	2.58	5.00	2.42	....	5.856
20	95	0.28	0.50	0.22	....	0.048
21	100	0.14	1.00	0.86	....	0.740
	Totals	71.70	62.10	24.05	33.65	295.648

Data given by the International Institute of Agriculture (Rome), 1926, in its publication "The cotton growing countries, present and potential" for the proportional effect of the factors affecting the yield of cotton in a given soil show: Deficiencies or excess of water account for 15.84 per cent; other adverse elements of climate account for 4.60 per cent; insects and diseases account for 18.00 per cent.

The significance of water appears to be more than three times as large as that of all the other meteorological factors taken together. We also know that soil-evaporation, or reservoir-evaporation, depending on the aforementioned meteorological factors varies from year to year about one-half as much as precipitation. In column (4) of Table 1, I give the hypothetical rain that fell in a certain period of 450 days starting 21.4 days before October 1, when sugar-cane was sown in a Matanzas clay-soil. The amounts of water for each of the 21-day periods are supposed to have been corrected for intensity using escurrimetro-data. It is required now to measure the value, or we may say the effectiveness, of this rainfall-regime on the contemporary sugar-cane crop whose standard is given in column (3). We proceed to subtract the former from the latter, assigning a plus sign when the regime exceeds the standard, entering the differences in column (5). In column (6) the differences are squared.

From the sums of the two sub-columns of column (5) we may glean some information worth mentioning. The sum of the differences with a plus sign represents the total amount of the rainfall which occurred in excess of requirements. This excess cannot be taken as runoff as the figures of the regime were supposed to have been corrected for intensity. The total with the plus sign is water which actually penetrated the soil and which, because being in excess of that required for optima conditions, goes down in part to join the water-table and also contributes to increase the moisture-content of the soil above that which the crop requires. The plus sum, amounting to 24.05 inches, did not contribute to the well-being of the crop, but was either wasted by deep infiltration, or was a source of damage to the crop. Therefore, out of the total amount of the regime only (62.10 - 24.05) = 38.05 inches are to be taken as effective water.

We may also consider the sum with the negative sign which is 33.65 inches. This total represents shortages as the regime came far from meeting at all times the requirements of the standard. If supplemental irrigation were to be provided, this total stands for the minimum amount that would have been required in the particular year of observation.

It is thus seen that, because the opportunity-requirements of the standard total amount of

71.70 inches were not fulfilled, a rainfall-regime amounting to 62.10 inches, which is only 9.60 inches below the total called for by the stand, was equivalent only to 38.05 inches of effective water.

We should now turn our attention to establishing some summary measure or index which takes account of the total amount (corrected for intensity) as well as of the opportunity. I have only had very incomplete data at my command to test out which of several possible indices is best. Only experience can tell. Any of those given hereafter may prove the most satisfactory, and each has weak points.

Three different forms are presented which meet the following basic conditions: (a) Must be equal to one when the regime and the standard agree exactly; (b) must be zero when the regime shows the maximum possible difference with the standard.

Form of index A--The first index, which we may call (A), is based on the squares of the differences. The gross value for the illustrative example is the sum of column (6) of Table 1, that is, 295.648. But in order to fulfill conditions (a) and (b) it may take the form $[1 - \sqrt{\Sigma(\pi - \pi_R)^2 / \Sigma\pi + P_R^2}]$. Here $\Sigma(\pi - \pi_R)^2$ is the sum of the squares of the differences (295.648); $\Sigma\pi^2$ is the sum of the squares of each of the individual values of the standard excepting the last. This sum equals 4175; which includes P_R^2, the square of the sum of the regime = 62.10. Substituting, we obtain for the index 0.74.

If the regime agrees with the standard exactly $\Sigma(\pi - \pi_R)^2 = 0$ and the index is one. If the disagreement is to be maximum it is required that the total 62.10 of the regime be concentrated in one single term, corresponding to that where the requirement of the standard is lowest. This corresponds to $(\Sigma\pi^2 + P_R^2)$ as the value of the index; that is to say, for this case $\Sigma(\pi - \pi_R)^2 = \Sigma\pi^2 + P_R^2$. Strictly, instead of P_R^2 we should have $[P_R - (\text{minimum value of standard})^2]$ and instead of $\Sigma\pi^2$, $\Sigma(P - \text{minimum value})^2$. As all standards usually should have some very low elementary requirement (in the illustrative example it is 0.14) it is not worth while to take account of the differences.

We shall refer again to this quadratic index when referring to soils which are different from the standard soil.

Form of index B--The second index, which we may designate (B), may be called lineal, being based on the sum of the differences and not on the squares. The incorrect algebraic procedure of adding quantities, ignoring their signs, is a serious inconvenience of indexes of this kind. The gross value is, of course, the sum of the two sub-columns of column (5) of Table 1, that is, (24.05 + 33.65) = 57.70. In order that it may fulfill conditions (a) and (b) we may give it the form $[1 - \Sigma(\pi - \pi_R)/(P + P_R)]$, which gives one for complete agreement when $\Sigma(\pi - \pi_R) = 0$, and zero when P_R is concentrated in one single term. For the illustration this index has the value $[1 - (24.05 + 33.65)/(71.70 + 62.10)] = 0.57$. We shall again refer to this index later on.

Form of index C--Finally we may base the index in the partial positive and negative sums of the differences +24.05 and -33.65. We have already explained that (62.10 - 24.05) = 38.05 inches is the effective water or that part of the total of the regime which came within the requirements of the standard. It has a definite and important meaning. The negative sum stands for the total shortage of the regime, that is to say, when it did not supply the elementary amounts required by the standard. It is obvious, then, that we may also arrive at the effective water by subtracting this negative sum from the total amount of the standard, thus (71.70 - 33.65) = 38.05. Call the sum of the positive differences Σ_+, and Σ_- that of the negative ones. Then we may write for the index either of the two expressions $[(P_R - \Sigma_+)/P]$ or $(P - \Sigma_-)/P$.

In the first form, for complete agreement, there are no differences, then $\Sigma_+ = 0$; but also P_R must equal P, therefore the index is one. For maximum divergence P_R is concentrated in one term and, disregarding the small value for the minimum term of the standard, $P_R = \Sigma_+$ and the index is 0.

In the second form the optimum value is one, as $\Sigma_- = 0$. For the largest difference $P = \Sigma_-$ as there are 20 zeros in the regime for this case, so that the sum of the negative differences (standard exceeds regime) is equal to the total of the standard less the minimum value (0.14 in the illustration) which produces the positive sum. Strictly the zero-index results only in the case that one of the terms of the standard is zero but the difference from zero in practice will never be material as every standard has one very low term at least. For the illustrative example:

Index = $(P_R - \Sigma_+)/P$ = (62.10 - 24.05)/71.70 = 0.53. The second form, of course, gives the same value. If we take account of the small term 0.14 the maximum possible divergence which will be the same for either form is (62.10 - 52.10 + 0.14)/71.70 = 0.0019. This maximum applies to our standard. Different standards will give different maxima according to the value of the minimum term.

Variations in soil--The index as computed by any of the forms (A), (B), or (C) applied to the standard soil. If the soil be not standard, as is the case in actual practice, we must provide for the change in the value of the index as a consequence of change in soil.

It is not obvious how we can take account of the soil. It is believed that if everything else is the same, a change in soil means a modification of the standard. If the actual soil is lighter, the cane-crop may require more water to be supplied; but it would appear reasonable that the extra amount is a constant to be added to each of the elementary requirements of the standard. If the soil be heavier than the standard soil we should subtract some constant amount in the same manner. If we have to go actually over the process of modifying the basic standard by the constant amount and again subtract each of the 21 values of the regime from those of the new or corrected standard the process is not unreasonably long if we make use of indices of form (C). If indices of form (A) are, however, to be preferred it is time-consuming.

The desideratum would be a form of index which can be itself corrected (by some very simple operation) from its value computed for a standard soil, to that applying to any other soil.

Form (A), from the nature of the algebraic operations involved, does not lend to any such simple transformation, and it is to be noticed that it is at the same time the one which requires the largest amount of work.

Form (B) can be used and allows for the direct transformation in some cases; but the transformation cannot be worked out without previously ascertaining if it is possible, approximate only, or exact. As indices based on the illegitimate process of ignoring the signs of the differences are objectionable I shall drop this form with no further comments. [I should state, however, as a justification for considering (B)-indices that the objection of adding in a single total plus and minus differences which is not valid as an algebraic one, may be justified if equal defects or excess of water have the same limiting effect in the yield of crops.] The indices of form (C) can be transformed from the value they have for a standard soil to the value they must have for a different soil, provided that a change in soil can be taken into account by the simple process of adding or subtracting a constant amount to each of the 21 terms of the standard.

There may be other possibilities of taking into account the soil; but from the nature of the process given here, it appears unquestionable that any other possibility must also affect the standard requirements for the standard soil. The assumption that the modification is a constant may, however, not hold out in practice. Maybe the 21 elementary requirements are to be multiplied by some factor. Pending the application of actual tests based on reliable data I assume that the algebraic addition of a constant best takes care of the change in soil.

Having worked out the standard index (C) as 0.53 for the illustrative example, we may now turn our attention to the case where the soil is not Matanzas clay but some different type. The soil-factor may be based on some representative index. The water-holding capacity seems a proper one but it is given as a percentage and the correction must be in the form of some constant K, in inches. If δ be the water-holding capacity of the standard soil and δ_R that of the actual soil the difference $(\delta - \delta_R)$ may be taken as the basis for the correction which must be given as a percentage by volume.

Suppose the difference for any given soil amounts to five per cent. Let δ be 20 per cent and δ_R be 25 per cent. Reduced to inches of depth this means 0.20, which is to be subtracted from each of the 21 terms of the standard in this case, the actual soil holding more water than the standard.

If we use indices of form (A) or (B) we will have to subtract this 0.20 inch from every elementary requirement of the standard, and work the indices afresh. Employing one or the other of the sub-forms of form (C) we may work out the index for soil δ_R without actually going over the process as followed to arrive at 0.53.

We must know the number of terms in the standard where it exceeds the regime. The number of terms where it comes short of those of the regime are of course known from the constant relation $(N_+ + N_-) = 21$.

If the correction, as is the case, be subtractive we employ sub-form $(P_R - \Sigma_+)/P$. We need to consider only the positive differences and, the correction being subtractive in the standard, there is no possibility that a resulting difference can change from its position in the positive sub-column to that of negative sub-column, or vice versa. These possibilities appear when using indices (B).

We may, therefore, compute a (C)-index by the following simple operations: For $N_+ = 9$ with constant correction $K = 0.20$, the value of P for corrected standard is $(71.20 - 21)(0.20) = 67.50$; $\Sigma_+ = (24.05 + 9)(0.20) = 25.85$. Index $= (62.10 - 25.85)/67.50 = 0.537$ (subject to the same small error due to 0.14 in $P = 67$).

If sub-form $(P - \Sigma_-)/P$ be employed the outright correction, $-N_-(0.20) = -12(0.20)$, to the negative sum $\Sigma_- = 33.65$ will here give the correct value 31.25 and index $= (67.50 - 31.25)/67.50 = 0.537$. It is quite possible, however, that some element of the standard which is larger than the corresponding one in the regime by an amount smaller than the correction will cause the difference to change to the sub-column of the positive differences. To illustrate, suppose that in term (8) the regime instead of being 2.00 be 3.28. The difference is only nine but corresponds to sub-column minus. If we apply the correction -0.20 to the standard figure of 3.37, it will become 3.17, which is now smaller than the regime. The difference corresponds now to the plus sub-column. If we apply the correction +12(0.20) to the Σ_- sub-column we will be including this eighth term which is not now a part of the Σ_-. The number of terms which gives the Σ_- for the corrected standard would not be 12 but 11. In using form $[P_R - \Sigma_+)/P]$ there is no such possibility as the minus correction on the standard tends to enhance or increase the difference in the terms which in the uncorrected standard gives plus differences. In the former case a minus correction tends to approach the values of the terms changing the sign if the difference in the uncorrected standard comes within the value of the correction. These difficulties are apt to be troublesome for large corrections. For a negative correction we therefore always use form $[P_R - \Sigma_+)/P]$. If the correction be additive, we will have the same trouble with this form as we had with the form $[P - \Sigma_-)/P]$ for the subtractive correction. Therefore, we use this second form to compute the index if the correction be additive, as then it works in the same way as explained before for the subtractive correction.

If the correction for a change in soil must be proportional to the elementary amounts of the basic standard, there is no other way of arriving at the corrected index, whatever form we employ, than correcting the standard and working out the differences anew.

The index $[(P_P - \Sigma_+)/P]$ has a clear and definite meaning, being the relation of the effective water supplied by the regime, to that required by the standard.

We may write it as $(P_R/P - \Sigma_+/P)$, which shows the underlying structure. The portion (P_R/P) refers to the absolute amounts, as we would judge a rainfall-regime at present from the total amount. The second part depends on the opportunity of the occurrence; it is always negative and the index can never exceed the value (P_R/P), which in our example is 0.86. No matter how well the opportunity-requirements be met the shortage of $(71.70 - 62.10) = 9.60$ inches will not allow the index to go beyond the maximum value 0.86. Only if the quantity requirement be exactly met can the index increase to the maximum value for a perfect regime, that is, 1.00. The form $[(P - \Sigma_-)/P]$ has no such clear meaning and also P_R does not appear in the expression as shown. Therefore, the first one is to be used with the second form as an adjunct for transformation in case of varying soil. It might be argued that $[(P_R - \Sigma_+)/P]$ only depends on Σ_+ and does not take into account the shortages arising from changes in the regime with respect to the actual requirements of the standard. Because the regime comes short of meeting those requirements in 12 out of the 21 terms, the total shortage is 33.65 inches instead of 9.60 inches as would be judged from the total amount of 62.10 inches. But Σ_+ and Σ_- are necessarily linked up together and if there was no excess water in a regime with the same $P_R = 62.10$, the total of 24.05 occurring in our regime which causes the index to be 0.53 must, of necessity, be distributed among the terms which come short of the requirements of the standard, causing the negative differences to be less, and thereby increasing the index. As a matter of fact, if Σ_+ be 0 the value of Σ_- must be $(33.65 - 24.05) = 9.60$. From form $[(P_R - \Sigma_+)/P]$ the index is 0.86 if $\Sigma_+ = 0$ and as Σ_+ cannot be 0 (P_R and P remaining the same) unless Σ_- be affected exactly by -24.05 inches, the index computed from the second form, which takes account of the actual shortage, must also be 0.86. The Σ_+ and Σ_- are linked obviously by the same difference of P and P_R, that is, $(P - P_R) = (\Sigma_+ - \Sigma_-)$. As P and P_R are always given, if we take account of Σ_+ we also indirectly

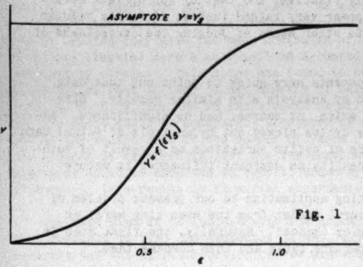


Fig. 1

take account of Σ_-. The index $[(P_R - \Sigma_+)/P]$ appears, therefore, as quite complete in itself, takes account of all facts, has a definite meaning, and varies between fixed limits for any values of P and P_R and for any form of distribution.

We may reasonably expect that if the yield of a crop shows a definite but usually low correlation with the total amount of water which it receives from seed to harvest which can be represented by $Y = f(P)$ it should be possible to compute Y with a much higher precision (as far as yield depends on the water-supply) from the relation Y is proportional to $[(P_R - \Sigma_+)/P]Y_S$, where Y_S is the yield corresponding to the standard water-supply in a standard soil. The form of the relation will not, of course, be as shown but if we call $(P_R - \Sigma_+)/P = \epsilon$, the index of effectivity of a certain rainfall-regime, $Y = f(\epsilon Y_S)$. A lineal relation between ϵ and Y is not probable, nor will that form express the facts in a practical way.

As the index ϵ need not be 0 in order that the yield will be nothing, but such low values of ϵ as 0.10 will probably give no yield, the locus of the function $Y = f(\epsilon Y_S)$ should approach the zero yield-limit tangentially and should also approach the Y_S limiting value in the same form. A correct expression for $Y = f(\epsilon Y_S)$ based on mathematical considerations alone is curve as shown in Figure 1. For very small values of ϵ, Y is practically zero; values of ϵ need not go beyond 1.00, or a little over, in order that $Y = Y_S$ very closely. There are objections mathematically to a theoretical upper limit at one. It is quite useless to go further. The actual form of the relation $Y = f(\epsilon Y_S)$ remains to be determined by actual experience.

The method outlined may be used also to give numerical form of expression to the application of irrigation-water. It was also applied to the runoff-experiments at Wagon Wheel Gap taking one of the years of observation as a basis for comparison. The dispersion improved considerably from that which occurs taking the total annual precipitation as the criterion. It is believed that some method based on similar lines of reasoning will assist very much in arriving at runoff from rainfall especially if escurrimetro-data are also used.

Republica de Cuba,
Ministerio de Agricultura,
Director de Industrias

LONG-TERM CONSTANCY OF RAINFALL

Carroll F. Merriam

Some years ago, when the theories of cyclic influence in rainfall were rather in disrepute, I urged against too precipitous abnegation of these ideas. Today I am seemingly taking the opposite position. Although apparently reversing myself, I feel that I am consistent in that both times I have advised a conservative course, a calm appraisal of the data before us, and above all the avoiding of extreme enthusiasm to which Americans are prone. I view with some alarm those predictions which are now being made with so much assurance that in such and such a year we are to expect unprecedented drought because in that year the low points of three long-term cycles are going to coincide.

Long-term cycles may exist, but I do not believe that as yet we have reliable data by which they can be identified with sufficient certainty. This lack of faith comes from a study of composite averages of annual rainfall in various sections of the northeastern portion of the country. Figure 1 shows the mass-departure curves for several large groups, and it will be noted that, although they are somewhat widely separated geographically, there are certain outstanding characteristics which persist throughout all of them. Note particularly the marked dip in the 70's and early 80's together with the sharp regain thereafter. In spite of this outstanding departure, all of them tend to hold to a rather even course and do not wander far from the mean line.

It can be said of course that all this is merely relative, and that by appropriate selection of vertical scale the curve could be made to appear very ragged instead of fairly regular. This is perfectly true, and therefore we must turn to other means of judging the correctness of this first impression.

When the theory of cycles was proposed, its opponents were quick to point out that data could be drawn by lot and subjected to the same kind of analysis with similar results. Sure enough, cycles, or apparent cycles, were thus found which, of course, had no significance. Although this form of reasoning did not prove that the cycles picked out by analysis of actual data did not exist, it did show that merely the appearance of cyclic variations as a result of mathematical treatment did not necessarily prove their reality as dominant influences in nature.

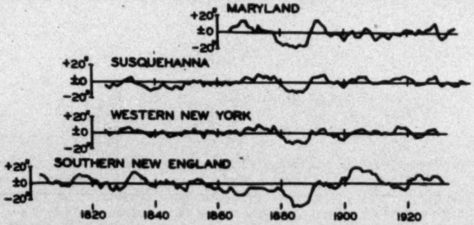
This use of a lottery as a test has an interesting application to our present problem by suggesting the question: "Does the mass-departure curve wander from the mean line more, or less, that it would if the data were arranged purely by chance?" Naturally, the first step is to draw the same data by lot, construct the mass-departure curve and then compare them.

This is done in Figure 2. The curve so derived from 200 drawings of the 137 values of the departures from the mean annual rainfall over the Susquehanna is compared with the actual sequence as arranged by nature.

Of course, no single test of this kind should be considered conclusive for the reason that by chance it is perfectly possible to get about any result. All that we can say so far is that it would appear as though the actual curve did stick more closely to the mean line than the same data drawn by lot. To be more certain of this conclusion it would be necessary to repeat this experiment over and over again, and even then it would be necessary to make comparison by eye rather than to have any real measure of the results.

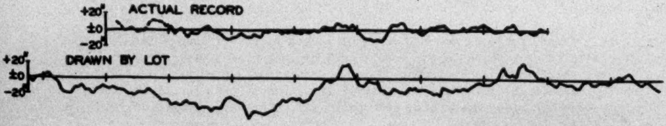
This would be rather tedious; and so another method was used which is intended to give a direct comparison between the actual arrangement and the result of an infinite number of drawings.

It was first found that the 137 values in the original, when arranged in order of magnitude, did give an excellent probability-curve (Fig. 3). This is quite symmetrical and at the midpoint the slope is easily found by graphical means. The first task is to draw a corresponding curve of distribution in order of magnitude for the algebraic sum of any two values in the original set. This could be accomplished by making 137 × 137 individual additions and arranging the



MASS-DEPARTURE CURVES OF RAINFALL

FIG. 1



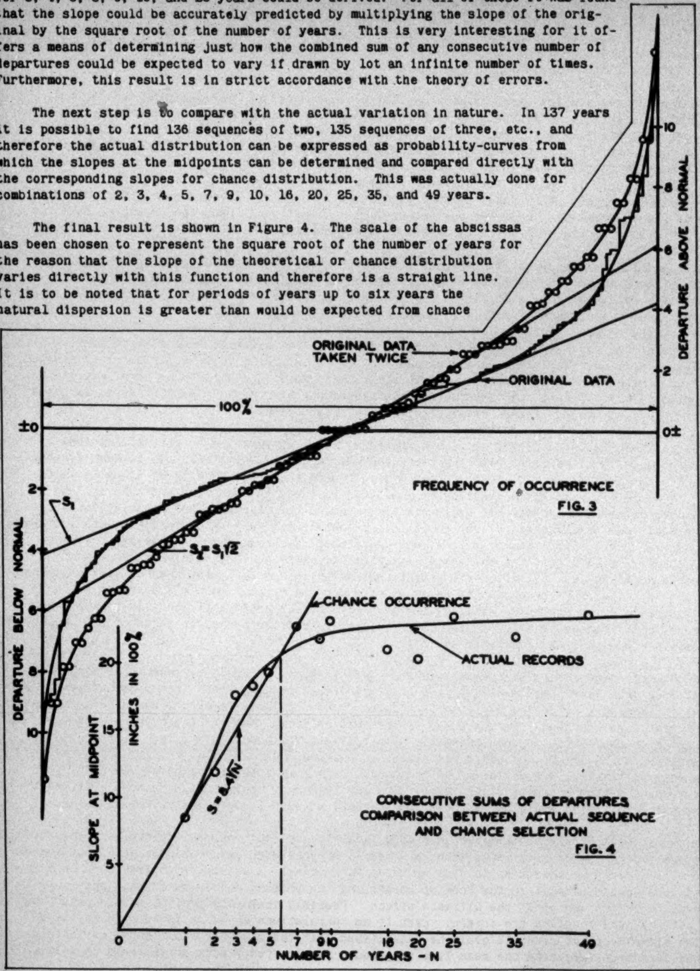
ACTUAL MASS-DEPARTURE CURVE COMPARED WITH SAME DATA DRAWN BY LOT

FIG. 2

18,769 sums as was done in the case of the original. This in itself would have proved rather tedious, so a short cut had to be found. We were not particularly interested in the ends of the curve but rather with the slope at the midpoint. Consequently, the work can be greatly simplified by dealing only with the mean ordinates of ten equal segments of the curve. The resulting 100 values likewise form a well-defined S-shaped curve with definite slope at the midpoint as indicated by circles. This slope was found to be exactly the slope of the original multiplied by the square root of two. Other numbers of values were tried in the same way so that the curves for 3, 4, 5, 8, 9, 16, and 25 years could be derived. For all of these it was found that the slope could be accurately predicted by multiplying the slope of the original by the square root of the number of years. This is very interesting for it offers a means of determining just how the combined sum of any consecutive number of departures could be expected to vary if drawn by lot an infinite number of times. Furthermore, this result is in strict accordance with the theory of errors.

The next step is to compare with the actual variation in nature. In 137 years it is possible to find 136 sequences of two, 135 sequences of three, etc., and therefore the actual distribution can be expressed as probability-curves from which the slopes at the midpoints can be determined and compared directly with the corresponding slopes for chance distribution. This was actually done for combinations of 2, 3, 4, 5, 7, 9, 10, 16, 20, 25, 35, and 49 years.

The final result is shown in Figure 4. The scale of the abscissas has been chosen to represent the square root of the number of years for the reason that the slope of the theoretical or chance distribution varies directly with this function and therefore is a straight line. It is to be noted that for periods of years up to six years the natural dispersion is greater than would be expected from chance



FREQUENCY OF OCCURRENCE

FIG. 3

CONSECUTIVE SUMS OF DEPARTURES
COMPARISON BETWEEN ACTUAL SEQUENCE
AND CHANCE SELECTION

FIG. 4

selection. Here the curves cross and beyond this point the slopes from actual sequences are not only less, but note that for the higher number of years there is little further increase. (In dealing with arrangements by lot, it was assumed that when a value was once drawn out of the hat it was replaced and so could be drawn again indefinitely. In this way the average of those numbers from which further drawings could be made would remain constant. This was necessary to permit the short-cut approximation without undue complication. In the natural sequence, where there is a definite number of values which can be used but once, the curve must necessarily return to zero when $X = \sqrt{137}$. It will also have the same ordinate for $X = \sqrt{136}$ as for $X = \sqrt{1}$, the same for $X = \sqrt{135}$ as for $X = \sqrt{2}$, etc. Consequently, it has a falling branch which is rather steep. A special study has since been made to determine to what extent this restriction may influence the ordinates of the curve in Figure 4, and it was found that it will by no means account for the marked flattening off shown.)

So far the results are based on far too limited experience to draw sweeping conclusions, and therefore they must be looked upon as indicative rather than conclusive. However, they at least open some new fields for endeavor in the study of climatic variations. It would appear that for short periods the wet and the dry years, as the case may be, tend to group together in a manner more pronounced than would be expected from mere chance coincidence. This effect may or may not be cyclic in nature, but at least it is an interesting observation for which the cause should be sought. For longer periods it would seem that the reverse were true, and that in the course of somewhat longer periods the opposites tended to attract each other so that the total variation from the mean would be less than expected from strictly fortuitous arrangement.

Although further evidence is obviously needed, is it too early to suggest as a hypothesis that the primary source of supply of water available for rainfall is relatively constant and consists of a rather uniform evaporation from oceanic surfaces? This water is "squeezed out" of the atmosphere in a somewhat irregular manner by the storm-making elements. From this it would follow that the amount in storage held by the atmosphere would vary somewhat in the manner of the mass-departure curve. As the supply becomes depleted from abundant rainfall, it would naturally be difficult for storm-making elements of given intensity to make further withdrawals because of limitations in the capacity of the air to hold more than a definite supply of water. Is it not possibly for some such reason that the mass-departure curve does not vary as far from the mean line as it would if the annual figures were drawn by lot?

Even without implying belief in such a proposal, it is interesting to contemplate some of the consequences. In the first place to establish beyond doubt such a relation between evaporation and rainfall would in itself constitute a step toward the understanding of climatic variations. It would imply that fluctuations were not merely local in character but more or less general over rather wide areas. It would also be expected that correlations could be found between rainfall and total moisture-content in the atmosphere together with other elements such as temperature and certainly stream-flow. In the past these relations may possibly have been obscured because little effort has been made to derive composite averages of large numbers of gages which would be less affected by observational error in any one. The general similarity of rainfall over rather wide areas, which would be necessary to support such a theory and which is certainly indicated in Figure 1, particularly in regard to the great deficiency in the 70's and 80's, would be a tremendous help in piecing in missing rainfall-records for parts of the country where data for the past are decidedly lacking.

In the matter of determining mean values for rainfall, if it could be shown that some sort of equalizing does take place over a period of time, it would follow that the number of years of observation necessary to derive a mean with a given degree of probable error, would be less than would otherwise be supposed. Furthermore, if it could be shown that the water to be expected over a given drainage-area depends primarily upon a relatively constant supply, but modified by irregularities which are reflected in variations in total water-content of the air, then the annual amounts of rainfall can no longer be considered purely accidental chance happenings. If this were so, a better estimate of the true value may be had by applying the principle of least squares, which in itself would bring about an important advance in determining normal values.

We cannot neglect the enticing subject of divination, or "fortune-telling" to be frank. If this apparent bunching of good years with good years, and bad with bad, could be verified, there must be some underlying reason which sets up these variations. A search of contemporary meteorological data should be made in the hope of unraveling the primary causes which must bear some signs which are forerunners of the ultimate effect. Possibly these are cyclic, possibly not, but in any case we need to probe the origin. Even if no correlations could be found with anything else, but after years of study it could be established that the mass-departure curve definitely undergoes less departure from the mean line than would result from random arrangement of values having the same probability of occurrence, then even though the cause still remained unknown, it could be reasoned that departure on one side or the other foreshadowed a probability of return to the established mean line. It could be said with assurance that the chances were at least better than even that the sign of the departure would be opposite to that for the years during which the departure had been built up. This last principle has an important bearing upon efforts to equalize correctly and in a scientific manner the financial results of enterprises which are in some measure dependent upon fluctuations in rainfall.

As for the long-term cycles, the foregoing does not in any way disprove their existence. However, it does indicate that even greater caution should be exercised. Throughout the derivation of the basic data for this study it became evident that systematic errors can easily lead to false and apparent cycles which prove on comparison with large numbers of other gages to have no substance. They appear merely as ghosts which for perfectly good mathematical reasons have the habit of camouflaging themselves in the form of true cycles. This danger is greatly increased as the period becomes longer. The fact that carefully built-up composite records indicate if anything a smoothing out rather than a tendency toward long periodic swings should be heeded as just another warning sign.

We are, therefore, in a position to meet a challenge. Perhaps we are enticed by a mere will-o-wisp which may lead us into a morass of uncertainty, but when we consider the consequences of a more definite knowledge of the fluctuations of rainfall it would seem that as scientists we should rise to meet it.

Pennsylvania Water and Power Company,
Baltimore, Maryland

DISCUSSION

Comments by CARROLL F. MERRIAM--The response to sending out of preprints of this paper brought a number of replies which have been of great assistance. Doubts were expressed as to the ability of the atmosphere to hold in storage sufficient water to account for the variations noted in the mass-departure curves. This is a valid objection to the tenability of the hypothesis proposed. If we are to consider merely the capacity of the atmosphere directly over a given area in the Temperate Zone, it is obvious that the extreme variations in water-content could amount to but a few inches.

The proposal was originally made to offer a possible explanation, more to serve as a starting point for further thought and investigation. It appears from the data analyzed so far that mass-departure curves of composites of a large number of gages seem reluctant to vary from the mean line as widely as would be expected from mere chance arrangement of the same data drawn by lot. They behave as though there were some equalizing force drawing the curve back to the normal line.

Although there are several considerations that may overcome the objections raised, and thus bring the hypothesis into the range of possibility, it is not essential that this should be accepted as the explanation. The point I wish to emphasize is that some equalizing force, whatever it may prove to be, seems to be operating.

It is believed that much misunderstanding arises from failure to comprehend the nature of the data that were used in this study. The curves for the various districts have been built up by a process of averaging to derive first a tentative standard, against which the individual gages were compared to get the factors which may in turn be used in multiplying the original data to derive a new standard. The data were then re-tested against this to find again more precisely these factors and also the times when the relationship changes abruptly. Again these multipliers were used to determine a third standard, and so on. The result is that even when the original data come from rather widely distant regions, the mass-departure curves bear a surprising resemblance to each other.

The striking feature is the closeness to which all of these curves conform to the normal line, which is to be contrasted with the variations that will be found when the same data are arranged by chance.

Some criticism has been rightly made that the curves in Figure 1 are not strictly independent of each other, for in the earlier years, when data are lacking, information had to be borrowed from distant sources. In the later years the curves become more independent of each other when this need for borrowing is relieved, but even at the end there are some gages which figure in both the Western New York and the Susquehanna curves. Likewise the curve marked Maryland is composed merely of the gages used in deriving the Susquehanna curve which happened to be located in Maryland.

HERBERT C. S. THOM (U. S. Weather Bureau, Washington, D. C.; communicated)--The author deserves to be commended for calling attention to certain problems in statistical climatology which are in need of further investigation. Unfortunately, the development of the theory of time-series has been somewhat unsatisfactory, and since sequences of annual rainfalls are time-series, little progress has been made in their analysis.

The author has resorted to some unique and rather difficult to comprehend statistical analysis in order to illustrate his points. In making the 200 drawings from the 137 departures and inferring that more should be drawn to obtain a more accurate conclusion, the author has failed to realize that the 137 values are in themselves only a sample from which, of course, no further information could be gleaned by successive drawings.

The author uses the slope at the center of the cumulative frequency- or distribution-curve of Figure 3 as a measure of the dispersion. However, the slope of a distribution-curve at its central point is not necessarily a measure of the dispersion; in fact, it is only in very exceptional cases that it is such a measure. This is the case for the "normal distribution" which fortuitously seems to be a good fit for the data from individual drawings of Figure 3. The slope at the center of the normal curve is $1/(\sqrt{2\pi}\sigma)$; thus the standard deviation $\sigma = 1/(\sqrt{2\pi}\, S')$ where $S' = (1/S)$ of the author's notation, and hence $\sigma = S/\sqrt{2\pi}$. The writer found the standard deviation for the individual drawings by the conventional method of computation to be 3.54. Using $S = 8.5$, as read from Figure 3, $\sigma = 8.5/\sqrt{2\pi} = 3.4$, which is a reasonable check when the inaccuracy of graphical methods are considered.

The author has gone to unnecessary trouble to find that the "dispersion" for the sums of samples of n drawn by lot is the $\sqrt{n}$ times the "dispersion" for a single drawing, it being shown in most elementary statistical texts that this is true regardless of the distribution. Dispersion is often defined as σ^2 rather than as the author has employed it.

The samples of five and 20 sequences, tested by the writer, seem to be about as close to a normal distribution as that for the individuals drawn by lot. The samples of five- and 20-year sequences, however, have a lesser dispersion than the individual drawings from which it can be inferred that there is a non-random effect in the individual sequences. From this it should be concluded, conversely to the author, that a given length of sequence actually furnishes less information regarding the true mean of the population than if the individual departures were random. Values of S in Figure 4 should be multiplied by $[n/(n - 1)]$ where n is the number of sequences; this will give a better estimate of S especially for the longer sequences.

Figure 2 shows one fact that could have been predicted without analyzing the data, that is, the dispersion for single trials in sequence as nature assembles them must always be less than that drawn by lot and therefore the mass-departure curve must always be closer to the mean than the series drawn by lot. This follows from the fact that assembling data as nature does the probability varies from trial to trial and thus a Poisson sampling series results. It can readily shown mathematically that the dispersion for a Poisson series must always be less than that for a Bernoulli series (drawing by lot).

The author's argument that the atmosphere is a reservoir of moisture is at least partly valid. Rainfall-variations are caused mainly by variations in the strength of the atmospheric circulation which in turn are caused largely by variations in temperature-gradient in the upper air. More intense circulation is accompanied by greater moisture-content of the air; so, granting that rainfall is correlated with precipitable water, there should be a good correlation between the circulation-strength and rainfall. (In some recent studies the writer correlated precipitable water and rainfall, and found squared correlation-coefficients of from 0.25 to 0.30.) This would seem to bear out the author's conclusions if they are interpreted to mean a reservoir of moisture-flow rather than simply a static reservoir of moisture, for the atmosphere is really never static but constantly in motion.

MEASUREMENTS OF THE FALL-VELOCITY OF WATER-DROPS AND RAINDROPS

J. Otis Laws

Introduction

This paper presents measurements of the velocities of water-drops of sizes ranging from one to six mm in diameter, falling in still air from heights of 0.5 meter to 20 meters. A few measurements of raindrop velocities are also reported.

The measurements were undertaken to assist in an understanding of the action of rain, both real and artificial, in eroding soil. The drop-sizes of rains have also been measured and will be reported separately. All of these studies were carried out at the Hydraulic Laboratory of the National Bureau of Standards as a part of the work of the Soil Conservation Service.

The velocity of falling raindrops and water-drops has been studied by several investigators in the past. The most complete measurements are those of P. Lenard [see 1 of "References" at end of paper] and Wilhelm Schmidt [2].

Lenard measured the velocities of drops with diameters of 1.28 to 6.36 mm by suspending them in the blast of a fan and measuring the air-velocity at the point of suspension. He measured the size by catching the drops on a sheet of absorbent paper as they slipped out of the air-stream. From the size of the water-spot he determined the size of the drop, following the method of drop-size measurement used by most European observers. Defant [3] made the most thorough study of this method of drop-size measurement.

Schmidt measured the velocity of raindrops ranging in diameter from 0.4 to 3.5 mm with an ingenious apparatus consisting of two discs mounted on an axle and turned at a known rate. A raindrop, which by chance fell through a small sector cut in the upper disc, would land upon a piece of absorbent paper laid on the lower disc and turning with it. The location of the spot relative to the projection of the sector on the paper gave a measure of the velocity, while the diameter of the spot gave a measure of the drop-size.

H. Mache [4] made a few measurements photographically but he had no way of finding the size of the drops whose velocity he measured. Mache's work deserves mention primarily because a modification of his method was used in the present measurements.

The measurements reported here were undertaken primarily to obtain data on the velocities of drops falling through the relatively small distances that it is practicable to use in producing artificial rains. The data gathered on raindrops served as a direct check upon the measurements of Schmidt. The measurements indoors at heights of fall where the velocity can be regarded as terminal offer a check upon Lenard's measurements.

The measurements reported here show a surprisingly large deviation from the measurements of Lenard and Schmidt, whose results closely confirmed each other. Velocities fully 15 per cent higher were observed. Finding no appreciable errors in the present measurements, it is the author's conclusion that the values observed over 30 years ago and accepted unquestioningly since, are in error by large amounts.

Methods of measurement

Camera and light-box--The measuring apparatus consisted of a 9 by 12 cm still camera mounted behind a "chopper-disc," driven by a small synchronous motor. In front of this a collimating lens was mounted at a distance equal to its focal length from the center of the lens of the camera. This had the effect of making objects on the other side of the collimating lens appear the same size regardless of their distance from the camera. Dark-field illumination was accomplished by a light-box employing over-run lamps arranged in such a way that light was directed toward the camera from either side on the field of view. Strips of sheet metal were placed in front of the collimating lens to reduce the amount of light absorbed on its surface. An opening of four by five inches was left in the light-box for drops to fall through. The camera side of the collimating lens was shielded from the light of the room by a conical casing.

The use of dark-field illumination and a "chopper-disc" made it possible to obtain multiple images of a drop on a single film. The arrangements of the light and the camera are shown in Figure 1.

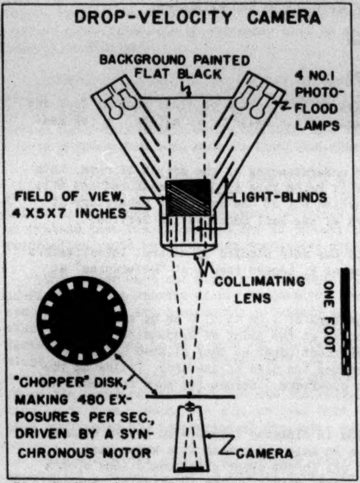

DROP-VELOCITY CAMERA
BACKGROUND PAINTED FLAT BLACK
4 NO. I PHOTO-FLOOD LAMPS
FIELD OF VIEW, 4 X 5 X 7 INCHES
LIGHT-BLINDS
COLLIMATING LENS
ONE FOOT
"CHOPPER" DISK, MAKING 480 EXPOSURES PER SEC., DRIVEN BY A SYNCHRONOUS MOTOR
CAMERA

Fig. 1--Velocities of drops were measured by means of a still camera fitted with rotating-disc shutter driven by synchronous motor and making 480 exposures per second; dark-field illumination was employed, and collimating lens was interposed between subject and camera to eliminate magnification errors

Magnification error--The magnification of the combined lenses was determined by photographing a millimeter-ruled cross-section paper in the center of the field of the camera, the paper being held between two glass plates in a plane normal to the camera's axis. The accuracy of the rulings was checked just before photographing. Measurements from the developed film by means of a micrometer-microscope showed the magnification in the center of the field to be 1/2.544.

The magnification at different positions in the field was determined by the same method with the following results: Magnification 0.5 inch from the light-side of the opening, 1/2.548; magnification 3.5 inches from the light-side of the opening, 1/2.539. The maximum error, therefore, to be expected from this source is about 0.2 per cent, which was considered sufficiently accurate although the optical system was capable of even greater precision. If the collimating lens had not been used the deviation from the average magnification would have been eight per cent.

J. M. Slater [5], who suggested the use of such an optical system, has described the optical characteristics of similar systems in a recent issue of Photo Technique.

The shutter--The timing device was a single-phase, 1/150-horsepower synchronous motor which turned at 30 revolutions per second on a 60-cycle alternating current. The motor was plugged into the lines of the Potomac Electric Power Company. The generators of this Company are tied in with the so-called "eastern system." The frequency of this current is carefully regulated and believed to be constant within a few tenths of one per cent. To ascertain whether the motor, for any cause, was not turning in synchronism with the current when the "chopper-disc" was mounted, the motor was placed in a dark-room and illuminated by a neon-lamp, under which illumination the screw-heads of the hub appeared to be stationary, which would only occur when the motor was turning in synchronism with the current. It was observed that considerable braking force had to be exerted before the motor "lost step" as indicated by an apparent slow counter-rotation of the screw-heads.

The "chopper-disc" was made from a paper chart designed for use on a water-stage recorder. Out of this circular sheet, which was 11-1/8 inches in diameter, 16 sectors were cut 1/4 inch from the rim, each sector measuring one by 7/8 inch. Both sides of the sectors were carefully cut along the printed radii of the chart. The disc was then painted black.

Taking the picture--To take a picture with this apparatus, the motor was started, the lights were turned on, and the camera-shutter was opened for a short interval of time. It was desirable to have as many drops as possible on a single negative, but if the exposure was too prolonged the light absorbed on the imperfectly shielded collimating lens obscured the drop-image. For this reason, an exposure of approximately two seconds was the maximum that could be used.

The aperture opening was set at f/8. The film used was Agfa Super Pan Press. It was developed for maximum contrast.

Measuring velocity from negative--The image of each drop appeared as a pair of broken lines (see Fig. 2). The partitions in the "chopper-disc" obstructed the light many times during the drop's passage through the illuminated dark field. The two lines of the image were due to highlights which appeared on either side of the drop.

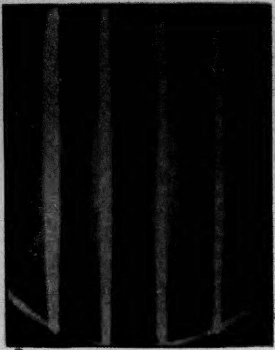


Fig. 2--Typical velocity photograph obtained with this camera; light blinds immediately in front of the collimating lens appear as bright vertical streaks; broken double lines are blurred images of falling drops, the drops having moved during exposure; each drop produces a double-line image due to manner in which it was illuminated

To determine the velocity, the distance between the tips of two drop-images was measured. The points of a pair of dividers were fitted to two images on the negative as far apart as possible; the "drop-negative" was then replaced by a negative of the cross-section paper. The distance, h, as indicated by the points of the dividers was read to the closest half mm. The number, n, of breaks in the double line were then counted. Since the motor turned at 30 revolutions per second and the "chopper-disc" had 16 openings, the film was exposed 30 × 16 = 480 times a second, or the time elapsed between the points of measurement is $t = (n/480)$. Therefore, the average velocity over this interval is $v = (h/t) = (480\ h/n)$. A correction for a slight error in the ruling of the cross-section paper photographed and used as standard of measurement was thrown into the coefficient, and the actual formula used in computing the velocity was $v = 4.81(h/n)$. When h is expressed in cm this formula gives the velocity in meters per second.

Measuring diameter from the negative--The precise determination of the diameter of the drop from the negative proved to be impossible. The high-lights on either side of the drop produced an halation on the film that varied with position in the field, velocity, and possibly, exposure, development, etc. Although several schemes of measurement were tried, none was found that gave consistent results within the rather narrow limits necessitated by this study. This unexpected shortcoming of the apparatus severely limited its utility, in so far as it necessitated the use of independent methods of measuring the drop-size.

Independent measurement of drop-size--This measurement was accomplished by allowing water to drip from glass tubes of small diameter, made by heating and drawing out glass tubing. Such a capillary was fitted to a filtering flask which was suspended above the raindrop-camera and the flow through the dripping tube was controlled by a screw-clamp. Drops were allowed to fall as fast as they could be conveniently counted--from two to three drops per second. Immediately before taking a photograph, a weighing bottle was placed under a capillary and 10 to 30 drops were collected. These were weighed on an analytical balance and the mass of the average drop was computed. Evaporation from the weighing bottle was checked and corrections were applied when necessary.

By this means drops ranging from 1.17 to 6.1 mm were obtained. The production of drops smaller than three mm by this method necessitated the use of extremely small aperture, and pressure often had to be applied to the filtering flask. To prevent the drops from wetting the outside of the tube and to decrease the friction along the tube-walls, the inside and outside of these capillary tubes were coated with a thin layer of paraffin. This was accomplished by applying a vacuum to the capillary and dipping it momentarily into molten paraffin.

Before this later technique was developed a number of measurements were made of 2.3-mm diameter drops by forcing water through an uncoated capillary at a high rate of dripping--8 to 15 drops per second. In order to determine the drop-size under these conditions the rate of dripping was determined by passing a piece of blotting paper under the capillary for a given interval of time and counting the number of spots. The weighing bottle was then placed under the capillary for a measured interval of time. These measurements were not precise and the drops seemed to vary in size. A disproportionate variability appears in the data obtained by this method (see Fig. 5-b).

The usual procedure for measuring drop-size did not give exactly the right value for the six-mm drops, due to a secondary drop which is produced at the instant of breaking away from the capillary and which fell into the weighing bottle along with the principal drops. Their size was roughly determined from measurements on the film, and a correction was applied although it amounted to less than one per cent.

Unreported measurements of very small drops--Several measurements were made of sprays composed of small drops but in these measurements no precise data were obtainable on their size.

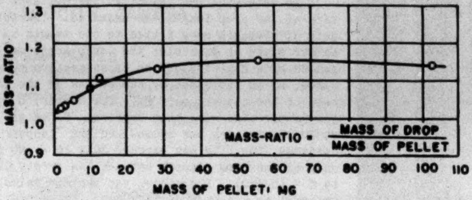


Fig. 3--Above relationship found to apply to Gold Medal flour used in these measurements; it was determined by allowing water to drip from small glass tubes into a pan of flour; size of artificial drops was determined by catching a counted number and weighing; air-dry pellets were desiccated for 60 minutes at 110° C; relationship varies slightly from one sack of flour to the next of same brand

These measurements were not considered sufficiently exact to report.

Adaptation of apparatus to measurement of raindrop-velocities--In order to adapt this photographic apparatus to the measurement of velocities of raindrops, a means had to be provided for measuring the size of the individual drops photographed. A shelter was built on the roof of the Hydraulic Laboratory, and the camera and its light-box were placed directly under a 4-inch by 5-inch opening in the roof of this shelter. The opening was insulated from splashes by grill-work extending one foot out in all directions and was provided with a cover which could be removed by the operation of a lever extending inside the shelter.

The camera and the light-box were provided with a broad belt with apertures so arranged that, by drawing this belt across the opening in the light-box, the field of the camera could be briefly exposed to the rain and, with the same movement, the film could be exposed. The apertures in the belt were so spaced that no drop could pass through the field without the film being exposed to it. A pan of uncompacted and calibrated flour was placed under the light-box in a position to catch any drop that fell through the camera's field. By drying and weighing the pellets of dough, formed by the drops in the flour, the size of the drops themselves could be calculated (see Fig. 3). This technique of drop-size measurement was first used by Bentley [6]. The details of making such size-measurement will be discussed in a separate paper.

If the camera's field was not too long exposed to the rain, the few pellets found in the flour could be associated with the impressions found on the negative by the size and location of each. When too many drops fell through, the association of pellets and impressions became dubious and the film had to be discarded.

Successful measurements could only be made on fairly large raindrops falling nearly vertical. All drops approaching the apparatus from angles greater than 30° fell outside the camera's field. Single pellets of drops smaller than two or three mm were difficult to weigh with sufficient precision. The chief limitation of this arrangement was the time required to obtain data on adequate range of sizes. While many large drops were present in some of the rains photographed, we were not fortunate enough to capture them in the extremely small samples peculiar to this apparatus. The vertical components of the velocities are reported in Figure 6.

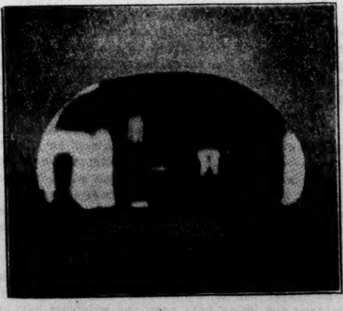


Fig. 4--Photograph of large waterdrop falling through still air by H. E. Edgerton; confirms observations of previous investigators who concluded falling drops were flattened rather than "stream-lined" as commonly supposed

Hygrometric measurements--Hygrometric and barometric data were taken in conjunction with

Table 1--Test-data

(D = diameter of a sphere equal in volume to the drop; H = height of fall; v = velocity of fall; t = temperature of air (dry bulb); t' = wet bulb temperature; B = barometric pressure; ν = kinematic viscosity of air)

D, mm	H, meters	V, m/sec	t, °C	t', °C	B, mm Hg	ν, (cm^2/sec)
1.15-	0.53	2.74	21.0	13.3	752	0.153
1.19	0.98	3.48	21.0	13.3	752	0.153
	0.98	3.47	21.0	13.3	752	0.153
	0.98	3.44	21.0	13.3	752	0.153
	1.50	3.87	21.0	13.3	752	0.153
	2.50	4.28	21.0	13.3	752	0.153
	4.50	4.60	21.0	13.3	752	0.153
1.74	0.50	2.84	23.0	15.3	748	0.156
	0.50	2.85	23.0	15.3	748	0.156
	1.50	4.36	23.0	15.3	748	0.156
	1.50	4.38	23.0	15.3	748	0.156
	2.5	5.12	23.0	15.3	748	0.156
	3.46	5.49	23.0	15.3	748	0.156
1.73	4.5	5.69	23.0	15.3	748	0.151
	6.0	5.86	23.0	15.3	748	0.151
	8.0	5.90	23.0	15.3	748	0.151
2.28	0.5	2.94	25.0	19.5	764	0.155
	0.5	2.94	25.0	19.5	764	0.155
	1.0	3.93	25.0	19.5	764	0.155
	1.0	3.95	25.0	19.5	764	0.155
2.29	1.18	4.33	21.7	10.6	763	0.152
	1.18	4.33	21.7	10.6	763	0.152
	1.18	4.31	21.7	10.6	763	0.152
	1.18	4.31	21.7	10.6	763	0.152
2.28	1.5	4.67	25.0	19.5	764	0.155
	1.5	4.67	25.0	19.5	764	0.155
2.29	1.89	5.10	21.7	10.6	763	0.152
	1.89	5.08	21.7	10.6	763	0.152
	1.89	5.12	21.7	10.6	763	0.152
	1.89	5.12	21.7	10.6	763	0.152
	1.89	5.05	21.7	10.6	763	0.152
	1.89	5.05	21.7	10.6	763	0.152
2.28	2.0	5.15	25.0	19.5	764	0.155
	2.0	5.14	25.0	19.5	764	0.155
	2.0	5.13	25.0	19.5	764	0.155
	2.5	5.53	25.0	19.5	764	0.155
	2.5	5.49	25.0	19.5	764	0.155
2.38	2.81	5.72	21.7	10.6	763	0.152
	2.81	5.80	21.7	10.6	763	0.152
	2.81	5.66	21.7	10.6	763	0.152
2.28	3.0	5.83	25.0	19.5	764	0.155
	3.5	6.05	25.0	19.5	764	0.155
2.38	3.71	6.21	21.7	10.6	763	0.152
	3.71	6.23	21.7	10.6	763	0.152
	3.71	6.23	21.7	10.6	763	0.152
	3.71	6.18	21.7	10.6	763	0.152
	4.68	6.36	21.7	10.6	763	0.152
	4.68	6.47	21.7	10.6	763	0.152
	4.68	6.50	21.7	10.6	763	0.152
	4.68	6.28	21.7	10.6	763	0.152
2.32	5.51	6.66	24.0	15.9	761	0.154
	5.51	6.66	24.0	15.9	761	0.154
	5.51	6.64	24.0	15.9	761	0.154
2.34	6.51	7.06	24.0	15.9	761	0.154
	6.51	7.03	24.0	15.9	761	0.154
	6.51	7.03	24.0	15.9	761	0.154

Table 1--Test-data--Continued

D, mm	H, meters	V, m/sec	t, °C	t', °C	B, mm Hg	ν, (cm^2/sec)
2.34	7.50	6.92	24.0	15.9	761	0.154
	8.56	7.06	24.0	15.9	761	0.154
	10.8	7.06	24.0	15.9	761	0.154
	11.2	7.06	24.0	15.9	761	0.154
	13.0	7.07	24.0	15.9	761	0.154
	13.0	7.08	24.0	15.9	761	0.154
	13.0	7.08	24.0	15.9	761	0.154
3.02	0.24	2.12	....	....	...	.....
	0.24	2.12	....	....	...	.....
	0.24	2.13	....	....	...	.....
	0.50	2.96	....	....	...	.....
	0.50	2.98	....	....	...	.....
	0.50	3.01	....	....	...	.....
	0.50	2.97	....	....	...	.....
3.08	0.50	3.04	23.6	15.0	756	0.151
	0.50	3.03	23.6	15.0	756	0.151
	0.50	3.04	23.6	15.0	756	0.151
	0.50	3.05	23.6	15.0	756	0.151
3.02	0.97	4.09	....	....	...	.....
	0.97	4.07	....	....	...	.....
	0.97	4.07	....	....	...	.....
3.08	1.0	4.13	23.6	15.0	756	0.153
	1.0	4.13	23.6	15.0	756	0.153
	1.0	4.16	23.6	15.0	756	0.153
	1.0	4.15	23.6	15.0	756	0.153
3.05	1.05	4.18	25.0	21.9	...	.....
	1.50	4.79	25.0	21.9	...	.....
3.08	2.02	5.40	25.0	21.9	...	.....
	2.02	5.45	25.0	21.9	...	.....
	2.02	5.40	25.0	21.9	...	.....
	2.50	5.73	25.0	21.9	...	.....
	2.50	5.80	25.0	21.9	...	.....
	3.01	6.18	25.0	21.9	...	.....
	3.01	6.14	25.0	21.9	...	.....
	3.50	6.53	25.0	21.9	...	.....
	3.50	6.43	25.0	21.9	...	.....
	3.79	6.61	25.0	21.9	...	.....
	3.79	6.67	25.0	21.9	...	.....
3.02	4.02	6.74	21.0	....	755	.....
	4.02	6.79	21.0	....	755	.....
	4.02	6.79	21.0	....	755	.....
	4.50	7.00	20.7	....	744	.....
	4.50	7.00	20.7	....	744	.....
	4.50	7.00	20.7	....	744	.....
	5.04	7.16	21.0	....	755	.....
	5.04	7.16	21.0	....	755	.....
	5.04	7.16	21.0	....	755	.....
	5.49	7.22	21.0	....	755	.....
	6.00	7.48	21.0	....	755	.....
	6.00	7.42	21.0	....	755	.....
	6.50	7.49	21.0	....	755	.....
	6.50	7.51	21.0	....	755	.....
	7.00	7.57	21.0	....	755	.....
	7.50	7.70	20.7	....	744	.....
	8.00	7.79	20.7	....	744	.....
	8.00	7.82	20.7	....	744	.....
	8.00	7.82	20.7	....	744	.....
3.00	10.00	7.90	24.8	21.2	756	0.156
	10.00	7.82	24.8	21.2	756	0.156
	12.00	7.94	24.8	21.2	756	0.156
	12.00	7.96	24.8	21.2	756	0.156

Table 1--Test-data--Continued

D, mm	H, meters	V, m/sec	t, °C	t', °C	B, mm Hg	ν, (cm^2/sec)
3.00	14.00	8.08	24.8	21.2	756	0.156
	14.00	8.03	24.8	21.2	756	0.156
	16.00	8.09	24.8	21.2	756	0.156
	16.00	8.15	24.8	21.2	756	0.156
	18.04	8.11	24.8	21.2	756	0.156
	18.04	8.11	24.8	21.2	756	0.156
	20.0	8.11	24.8	21.2	756	0.156
3.92	0.88	3.97	25.0	19.0	762	0.155
	0.88	3.96	25.0	19.0	762	0.155
	1.36	4.81	25.0	19.0	762	0.155
	1.36	4.83	25.0	19.0	762	0.155
	1.88	5.47	25.0	19.0	762	0.155
	2.38	6.04	25.0	19.0	762	0.155
	2.38	6.02	25.0	19.0	762	0.155
	2.88	6.43	25.0	19.0	762	0.155
	2.88	6.35	25.0	19.0	762	0.155
	3.39	6.81	25.0	19.0	762	0.155
	6.00	8.00	21.6	16.1	750	0.154
	6.00	8.04	21.6	16.1	750	0.154
	9.00	8.65	21.6	16.1	750	0.154
	9.00	8.62	21.6	16.1	750	0.154
	9.00	8.58	21.6	16.1	750	0.154
	12.00	8.73	21.6	16.1	750	0.154
	12.00	8.71	21.6	16.1	750	0.154
	12.00	8.83	21.6	16.1	750	0.154
	12.00	8.64	21.6	16.1	750	0.154
	12.00	8.70	21.6	16.1	750	0.154
	15.00	8.78	21.6	16.1	750	0.154
	15.00	8.77	21.6	16.1	750	0.154
	15.00	8.77	21.6	16.1	750	0.154
	18.00	8.87	21.6	16.1	750	0.154
	18.00	8.84	21.6	16.1	750	0.154
	20.00	8.88	21.6	16.1	750	0.154
	20.00	8.84	21.6	16.1	750	0.154
	20.00	8.82	21.6	16.1	750	0.154
	20.00	8.88	21.6	16.1	750	0.154
5.04	1.0	4.24	25.0	19.0	762	0.155
	1.5	5.16	25.0	19.0	762	0.155
	1.5	5.13	25.0	19.0	762	0.155
	1.5	5.14	25.0	19.0	762	0.155
	1.5	5.13	25.0	19.0	762	0.155
	2.0	5.82	25.0	19.0	762	0.155
	2.5	6.40	25.0	19.0	762	0.155
	2.5	6.35	25.0	19.0	762	0.155
	3.0	6.85	25.0	19.0	762	0.155
	3.0	6.92	25.0	19.0	762	0.155
	3.46	7.22	25.0	19.0	762	0.155
	3.46	7.17	25.0	19.0	762	0.155
5.00	6.00	8.45	21.6	16.1	750	0.154
	6.00	8.45	21.6	16.1	750	0.154
	6.00	8.45	21.6	16.1	750	0.154
	9.00	8.96	21.6	16.1	750	0.154
	9.00	8.96	21.6	16.1	750	0.154
	9.00	8.96	21.6	16.1	750	0.154
	15.00	9.07	21.6	16.1	750	0.154
	15.00	9.28	21.6	16.1	750	0.154
	18.00	9.20	21.6	16.1	750	0.154
	18.00	9.20	21.6	16.1	750	0.154
	18.00	9.20	21.6	16.1	750	0.154
	18.00	9.20	21.6	16.1	750	0.154
	18.00	9.35	21.6	16.1	750	0.154

Table 1--Test-data--Concluded

D, mm	H, meters	V, m/sec	t, °C	t', °C	B, mm Hg	ν, (cm^2/sec)
5.00	18.00	9.20	21.6	16.1	750	0.154
	20.00	9.28	21.6	16.1	750	0.154
	20.00	9.25	21.6	16.1	750	0.154
	20.00	9.28	21.6	16.1	750	0.154
6.19	1.00	4.33	24.0	....	762	.....
	1.50	5.24	24.0	....	762	.....
	1.50	5.20	24.0	....	762	.....
	2.25	6.23	24.0	....	762	.....
	2.25	6.20	24.0	....	762	.....
	3.00	6.85	24.0	....	762	.....
	3.00	6.86	24.0	....	762	.....
6.10	6.00	8.58	21.6	14.6	750	0.154
	9.00	9.15	21.6	14.6	750	0.154
	12.00	9.35	21.6	14.6	750	0.154
	14.00	9.38	21.6	14.6	750	0.154
6.14	16.00	9.53	21.6	14.6	750	0.154
6.05	17.20	9.15	22.8	20.3	764	0.153
	17.20	9.12	22.8	20.3	764	0.153
	17.20	9.21	22.8	20.3	764	0.153
	17.20	9.32	22.8	20.3	764	0.153
	17.20	9.17	22.8	20.3	764	0.153
	17.20	9.21	22.8	20.3	764	0.153
6.14	18.0	9.30	21.6	14.6	750	0.154
6.05	19.7	9.17	22.8	20.3	764	0.153
	19.7	9.23	22.8	20.3	764	0.153
6.14	19.85	9.35	21.6	14.6	750	0.154

most of the measurements indoors. Wet- and dry-bulb temperatures were read from a sling-psychrometer. The atmospheric pressure was determined by an aneroid barometer at the elevation of the camera.

Test-results

Indoor measurements--The results of the measurements indoors are presented in Table 1, where they are arranged in ascending order of drop-size and height of fall. These data have been plotted in Figures 5-a and 5-b.

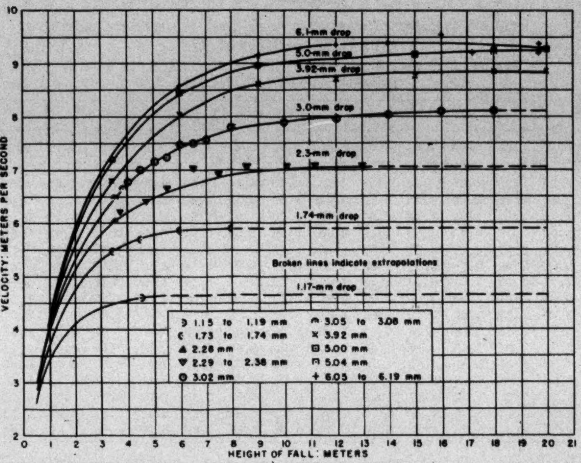
It was not always possible to obtain drops of exactly the same size. This necessitated drawing curves through data-points that are not strictly comparable. The drop-size represented by the curve is recorded along the curve.

In the summarization of these data a theoretical framework would be most useful; its derivation, however, is difficult. The general problem, of which this study is merely a special case, is that of expressing the resistance to motion encountered by an immersed body. A concise review of the more important work done on this problem from Newton to present-day investigators has been made by Rouse [7] in his "Nomogram for the settling velocity of spheres."

The deduction of a formula applicable to water-drops is complicated by the change in shape that the larger drops undergo during their fall. A falling water-drop is not tear-shaped, as is now well known, but quite oblate at terminal velocity as shown by the experiments of Lenard [1], as well as by some photographs of Professor Edgerton [12] of the Massachusetts Institute of Technology. During the first few meters of fall a large drop vibrates between vertical and horizontal oblateness with a frequency that depends upon its size. This oscillation is shown, quite incidentally, in Worthington's [8] remarkable photographs.

The frequency of the vibration of a water-drop was studied by Lord Rayleigh [9], who found $(4/D^2)$ oscillations per second, where D is the diameter of the drop in inches.

The effect of this change in shape is to add a new order of variation to a phenomenon already beyond the reach of current analytical tools. If the shape of the drop had been ascer-



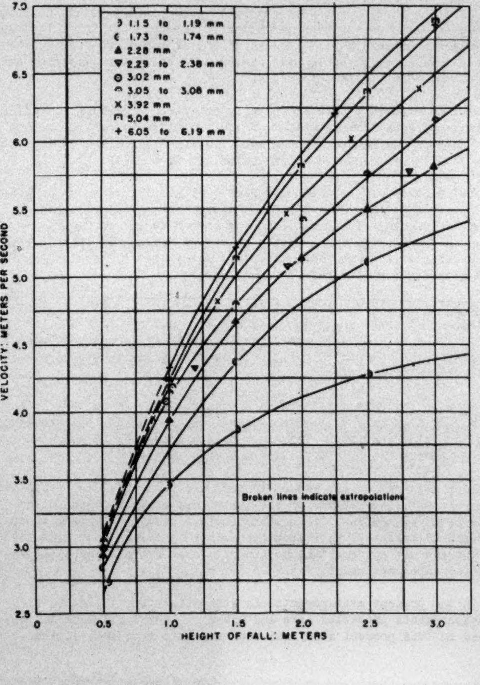


Fig. 5a--Velocity of fall of seven sizes of waterdrops after heights of fall of from 0.5 to 3.0 meters

Fig. 5b--Velocity of fall of seven sizes of waterdrops after heights of fall of from 0.5 to 20.0 meters

Table 2--Velocities of falling water-drops of different sizes after various heights of fall

(Velocity in meters per second; height of fall, H, in meters; diameter, D, in millimeters)

D	H											
	0.5	0.75	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	8.0	20
1.25	2.65	3.15	3.52	3.97	4.21	4.43	4.56	4.80	4.85	4.85	4.85	4.85
1.50	2.76	3.26	3.64	4.18	4.50	4.82	4.99	5.25	5.39	5.47	5.51	5.51
1.75	2.84	3.34	3.74	4.34	4.73	5.10	5.31	5.64	5.80	5.92	6.08	6.08
2.00	2.89	3.40	3.83	4.47	4.92	5.29	5.55	5.91	6.15	6.30	6.53	6.58
2.25	2.93	3.45	3.91	4.57	5.07	5.44	5.74	6.14	6.42	6.63	6.90	7.02
2.50	2.96	3.50	3.98	4.65	5.19	5.57	5.89	6.34	6.67	6.92	7.22	7.41
2.75	2.98	3.54	4.04	4.72	5.28	5.69	6.02	6.52	6.89	7.16	7.50	7.76
3.00	3.00	3.58	4.09	4.79	5.37	5.80	6.14	6.68	7.08	7.37	7.75	8.06
3.25	3.02	3.61	4.12	4.85	5.45	5.89	6.25	6.82	7.25	7.56	7.96	8.31
3.50	3.03	3.64	4.15	4.90	5.52	5.98	6.35	6.95	7.40	7.73	8.15	8.52
3.75	3.04	3.66	4.18	4.95	5.58	6.06	6.44	7.07	7.53	7.88	8.31	8.71
4.00	3.05	3.67	4.21	4.98	5.63	6.12	6.52	7.17	7.65	8.00	8.46	8.86
4.50	3.07	3.70	4.24	5.05	5.72	6.24	6.66	7.36	7.85	8.21	8.70	9.10
5.00	3.09	3.72	4.27	5.11	5.79	6.33	6.77	7.50	8.00	8.36	8.86	9.25
5.50	3.10	3.74	4.29	5.16	5.85	6.40	6.86	7.61	8.11	8.47	8.97	9.30
6.00	3.10	3.75	4.31	5.20	5.90	6.46	6.94	7.69	8.20	8.55	9.01	9.30

tainable from the photographs, it might have been possible to find an empirical relation between the coefficient of the resistance-formula and the Reynolds number. The computation of this number, however, requires a knowledge of the horizontal diameter of the drop and, therefore, the development of such an empirical formula, which would have served as a basis for comparing the data obtained under the various conditions, was not possible.

The original purpose of these measurements does not justify an extended rational investigation, but it is hoped such a study may some time be attempted. With a view to assisting such an endeavor, the hygrometric and barometric data have been included in Table 1. Liznar's [10] analysis of the data of Lenard and Schmidt is a good starting point for this study.

Lacking satisfactory rational equations, the data have been very simply presented in graphical form. Figure 7 shows the relation between velocity and diameter for various heights of fall. These curves were obtained by reading off values from the smooth curves of Figure 5. Table 2, in turn, has been prepared from Figure 7. Attempts to extend Table 2 to include smaller drop-sizes encountered complexities similar to those discussed above, and it was thought best to confine the Table to the range of experimentally determined values.

Measurements of raindrop-velocities--The few observations gathered on the velocities of raindrops have simply been plotted in Figure 6 and are not tabulated. A curve representing the values of Lenard and Schmidt as well as the curve representing the velocities observed indoors after 20-meter fall, have been plotted on the same Figure for comparison. The values represent the vertical component of the actual raindrop-velocities.

The tendency for the velocities of raindrops falling from great heights to be lower than the velocities of water-drops falling from only 20 meters indoors, may be due to the turbulence of the atmosphere through which the raindrops pass. The stray points appearing in the Figure are probably the result of having incorrectly paired pellets and drop-images.

The velocities found by Lenard and Schmidt are evidently much too low. The low velocities observed by Lenard may be due to excessive turbulence in the air-stream he used. Schmidt's method of measuring drop-size is open to question. In calibrating his absorbent paper, he appears to have overlooked the effect of height of fall upon the relation between spot-diameter and drop-diameter. This oversight was not as important in Lenard's measurements where the velocity of the drops relative to the paper was small.

Possible sources of error in the present measurements--In attempting to explain the discrepancy between the velocity-measurements presented here and those of Lenard and Schmidt, the technique of measurement employed in this present study has been examined from many angles.

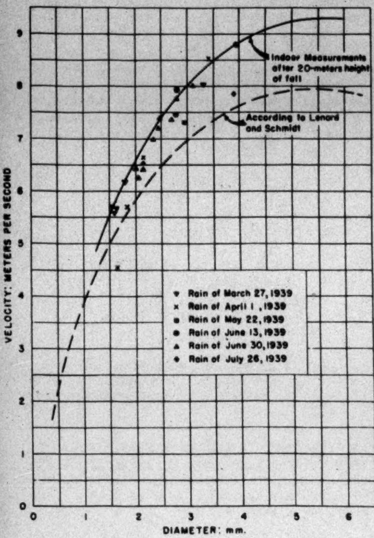


Fig. 6--Raindrop-velocity data, together with curves showing results of Lenard and Schmidt, and results obtained with waterdrops after 20 meters fall

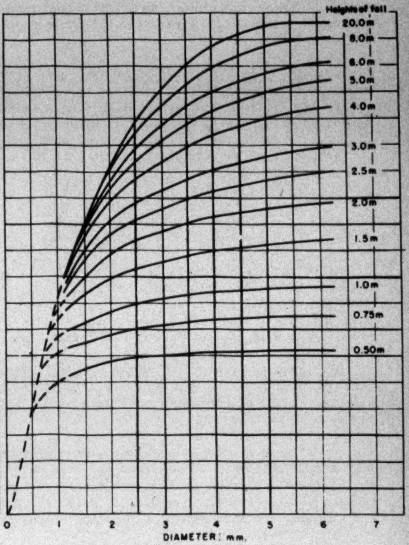


Fig. 7--Smooth curves showing relation between drop-diameter and velocity after 12 different heights of fall

Film-shrinkage, motor-speed, and magnification were checked and no appreciable error was found.

Evaporation from the drop-surface was also investigated. A few measurements of evaporation were attempted on large drops falling 15 meters. The drop-size was measured at the dripping tube by the usual method, and immediately afterward the drops were caught 15 meters below in a two-quart jar in the bottom of which several inches of flour had been placed to cushion the impact of the drops. This jar was capped and the drops were again weighed. No evaporation was detected in these crude measurements.

A study of evaporation by two Japanese is helpful in estimating the magnitude of this error. Namekawa and Takahashi [11] studied the evaporation of small water-drops in air and found the following formula:

$$(dR/dt) = -(\beta/R)(0.623\,\rho M/B)(p_1 - p_0)$$

where R = radius of drops, t = time, ρ = density of dry air, M = molecular diffusion-constant, B = barometric pressure, p_1 = saturation-pressure at the temperature of the evaporating surface, p_0 = vapor-pressure at the temperature and humidity of the air, and β = a function of the velocity of the drop relative to the air. CGS units were employed. The value of β was determined for drops of R = 0.085 cm for several velocities up to two meters per second. The results were expressed in the following empirical equation:

$$\beta = 1 + 0.21\sqrt{v}$$

the velocity, v, being expressed in meters per second.

Due to the limited velocities used in their experiments a bold extrapolation must be made in applying these results to our problem. If such an extrapolation is justifiable, the Namekawa formula indicates that the evaporation occurring in a few seconds of fall is negligible. The change in diameter calculated for a 1.74-mm drop after two seconds of fall was less than 0.1 per cent.

Height of fall required to attain terminal velocity--The question is often asked, "How far must a drop fall to reach a constant velocity?" Curves drawn to fit the experimental data approach the terminal value gradually, and it is difficult to decide at precisely what height they become coincident with the terminal value. The height required for drops to attain 95 per cent of their terminal velocity can be found with greater exactness and, for most purposes, should serve just as well. These heights of fall, as derived from the curves of Figure 5, are:

Size	Height	Size	Height
1-mm drop	2.2 meters	4-mm drop	7.8 meters
2-mm drop	5.0 meters	5-mm drop	7.6 meters
3-mm drop	7.2 meters	6-mm drop	7.2 meters

It will be observed that the five- and six-mm drops attain 95 per cent of their terminal velocity after shorter distances of fall than is required by the four-mm drop. Evidently, the necessary height of fall does not always increase with increasing drop-size. This is also true when the heights are read at 98 per cent of the terminal velocity and the trend doubtless applies also to the height required to attain the full terminal velocity.

Explanation of why large drops attain terminal velocities sooner than medium-size drops--This phenomenon is believed to be related to the apparent over-shooting of the terminal velocity observed in the 6.1-mm drop (see Fig. 5). It is too curious to be left without some attempt being made at explanation.

It will be observed that the 6.1-mm drop appears to approach finally a terminal value of 9.30 meters per second after about 20-meter fall. Drops of this size, however, were observed to be falling at the same velocity after only 10.5-meter fall. In the intervening distance, a drop of this size apparently increases in velocity until it attains a maximum of 9.40 meters per second at about the 14th meter, after which height it gradually slows down.

If this slowing down is real--and it appears to be--it is evident that the drop must have required time to attain its final shape. For, if changes in shape occurred concurrently with changes in velocity, the final value of air-resistance would have been acting on a drop of this size after 10.5-meter fall, and this force of resistance being equal and opposite to the force of gravity, would reduce the resultant force to zero. The drop would then have continued in a state of uniform motion.

Since the velocity of the drop continued to increase, its shape must have been such that it offered less resistance at 10.5 meters than it did at 20 meters, in spite of the fact that its velocity relative to the air was the same at both heights. It must be concluded, therefore, that changes in shape do not occur concurrently with changes in velocity, but that time is required for a given relative air-velocity to produce the final drop-shape corresponding to that velocity.

Lenard's observations led him to a similar conclusion. He writes: "It can be seen that they (large drops suspended in upward air-currents produced by a fan) are considerably deformed. The deformation flattens the drop vertically; this often continues in the large drops to a point where breaking-up occurs. Prior to this I have observed a similar deformation in natural rain by means of instantaneous illumination. The drops of the previous test showed no such deformation. It appears, therefore, that this deformation requires more time than was allowed in the previous tests where less than a tenth of a second elapsed. This corroborates the fact that the flattening of large suspended drops, in which the deformation occurs, begins only after an appreciable stay in the moving air.

"This time-lag is understandable if the deformation is not the result of pressure directed perpendicular to the drop-surface but of a tangential friction force of the air that brings the whole mass of the drop into circulatory motion which can only happen slowly because of the relatively large inertia of the water."

If such a lag is present, the reason why the large drops attain their terminal velocities at such small distances of fall is obvious. During the early stages of their fall, the large drops tend to remain spherical and, thus offering a smaller cross-sectional area to the passing air, attain, after small distances of fall, velocities higher than those consistent with their final shape. In the case of very large drops, the terminal velocity is actually exceeded. In drops of five mm, the terminal velocity is apparently never exceeded, but it is attained very early. This tendency is also evident in the four-mm drop, although less striking. The smaller drops are less easily deformed, and approach their terminal values of velocity more evenly.

References

[1] P. Lenard, Ueber Regen, Met. Zs., v. 21, pp. 248-262, 1904. (An English translation of this article may be obtained upon application to the Librarian, Soil Conservation Service.)

[2] W. Schmidt, Eine unmittelbare Bestimmung der Fallgeschwindigkeit von Regentropfen, SitzBer. Math. Naturwiss. Klasse K. Akad. Wiss., Bd. 118, Abt. IIa, Wien, 1909. (An English translation of this article may be obtained upon application to the Librarian, Soil Conservation Service.)

[3] A. Defant, Gesetzmaessigkeiten in der Verteilung der verschiedenen Tropfengroessen bei Regenfaellen, SitzBer. Math. Naturwiss. Klasse Akad. Wiss., Bd. 116, Abt. IIa, pp. 585-646, 1905.

[4] H. Mache, Ueber die Geschwindigkeit un Grosse der Regentropfen, Met. Zs., v. 39, p. 278, 1904.

[5] J. M. Slater, Perspective control in close up photography, Photo Technique, November, 1939.

[6] W. A. Bentley, Studies of raindrops and raindrop phenomena, Mon. Weath. Rev., pp. 450-456, October, 1904.

[7] H. Rouse, Nomogram for the settling velocity of spheres, Exhibit D, Rep. Comm. Sedimentation, 1936-1937, pp. 57-64, Nation. Res. Council, Div. Geol. Geog.

[8] A. M. Worthington, A study of splashes, Longmans, Green and Company.

[9] Lord Rayleigh, On the capillary phenomena of jets, Proc. R. Soc., v. 29, pp. 71-97, 1879.

[10] J. Liznar, Die Fallgeschwindigkeit der Regentropfen, Met. Zs., v. 31, pp. 339-347, 1914. (A translation of this article may be obtained by application to the Librarian, Soil Conservation Service.)

[11] T. Namekawa and T. Takahashi, Note on the rate of evaporation of small water-drops, such as raindrops, Mem. Coll. Sci., Kyoto Imp. Univ., Ser. A, v. 20, No. 4, July, 1937.

[12] E. K. Edgerton and J. R. Killian, Flash: Seeing the unseen by ultra-high-speed photography, Hale Publishing Company, 1939.

U. S. Department of Agriculture, Soil Conservation Service,
Auburn, Alabama

DISCUSSION

G. W. MUSGRAVE (Soil Conservation Service, Washington, D. C.)--This paper to me is extremely interesting, not only because of the unusual subject-matter but also because of certain ingenious and unique procedures which were used in the investigation itself. I think perhaps it has a more definite application in practice than may superficially appear. Although we can do very little in the way of changing the size of a drop of rain or the distance of fall, we may perhaps, under certain circumstances at least, do considerable toward protecting the land's surface.

We already know that the impact of beating rain may produce several effects upon the soil. Among these are: (a) The breaking of soil-aggregates and the destruction to a certain extent of the soil-structure near its surface; (b) a scattering of dispersed particles and, resulting from these, (c) a definite tendency to seal the openings in the ground's surface.

It is clearly apparent that there is a real need of protecting the land's surface from the impact of raindrops and we can readily see that the greater infiltration which is so commonly found in the presence of a dense grass-cover, for example, may be explained at least in part by the protective effects of the canopy which has been interposed.

Furthermore, we might at some future time ascertain during what seasons of the year the frequency of large drops is greatest and within certain limitations adjust the vegetal cover on cropland to provide the greatest protection when there is the greatest need.

The data of Laws of course permit the calculation of the total amount of energy which is applied to the surface by the rain and I believe he has made a number of calculations, all of which indicate that the amount of such energy is surprisingly large. I believe Mr. Laws has further studies under way which will give more definite information on drop-sizes occurring in natural rains.

EXTENDING THE FORECASTS OF TEMPERATURE FOR THE PREDICTION OF STREAM-FLOW FROM SNOW-MELT

R. K. Linsley
(Presented by title)

Introduction--Recent floods resulting from the combined runoff of rainfall and melting snow have brought this type of flood to the forefront of public consciousness in those regions where melting snow is an important contributing factor in floods. As a result, those who are assigned the responsibility of river-forecasting are receiving frequent requests for estimates of the potential flood-danger whenever a heavy cover of snow exists on a basin.

Such forecasts are of considerable value if they are wisely made and properly understood. The measures incident to flood-control, flood-relief, and flood-damage prevention are generally costly and cannot be continuously maintained. If, however, definite advice regarding the potential flood-hazard can be given the agencies interested, the necessary measures can be put into immediate action when and if the flood does materialize.

Potential flood-warnings--Properly, the information called for under the conditions being considered is not a forecast, for it does not state that a flood will occur, but rather that the flood could occur if critical conditions of weather were to develop. In this paper such warnings will be referred to as "potential flood-warnings" or simply as "warnings".

No special problem of river-forecasting is involved in the preparation of potential flood-warnings beyond those always inherent in river-forecasting. The validity of the warning hinges entirely on the prediction or assumption of critical conditions of weather. The greatest danger to be met in the preparation of such warnings is that often repeated, they become cries of "Wolf, Wolf", and are no longer heeded. If two basic requirements are met, this danger can be successfully avoided. They are:

(1) The warning must be based on a rational standardized procedure which will make all such warnings or advice for a given basin comparable, and in some measure provide the basis of comparison between two or more basins.

(2) The method must be thoroughly understood and its limitations appreciated by all to whom the warnings are issued. In order that the significance of the assumed critical conditions may be quite clear, they should represent a definite recorded experience of the basin under consideration.

The most commonly used procedure for the preparation of potential flood-warnings is for the forecaster to make assumptions of expected temperature and rainfall based on his judgment and experience, apply these melting influences to the existing snow-cover and from the estimated runoff develop a hydrograph. Very often this hydrograph must be further adjusted upward or downward on the basis of the forecaster's judgment. Although the final result may be quite reasonable under the conditions, the procedure fails to meet either of the two basic requirements established earlier. Such a method is far from standardized and the results gained by one forecaster are not comparable with those of another. Moreover, it is difficult to make the assumed critical conditions quite clear to those receiving the warnings. The assumptions often envision a period of critical temperatures and heavy rains at some future date with no attempt to connect these conditions with existing weather. Often no consideration is given to the possibility of a part or all of the snow-cover melting under the effect of moderate temperatures before the critical period is realized with the result that the flood-hazard is materially decreased.

Current weather-forecasts--Daily forecasts of weather now issued by the United States Weather Bureau indicate the expected maximum and minimum temperatures for 36 hours in advance. The forecast also includes a qualitative forecast of rainfall. On Tuesdays an extended forecast [see 1 of "References" at end of paper] is issued covering the four days ending Saturday night, and on Friday a forecast is issued covering the five days to the following Wednesday evening. These forecasts give the anticipated average temperature for the period in terms of normal, above or below normal, and much above or below normal. The limits of each range are defined by specific deviations from normal for all portions of the United States and each season of the year. The expected trend of the temperature about this predicted average is also given. From this information it is possible for the forecaster to construct a curve of predicted temperatures extending four or five days into the future. These forecasts show a natural decrease in accuracy as the end of the forecast-period is approached but, inasmuch as they represent the judgment of meteorologists who are applying the latest scientific methods available, they are believed to represent the most probable conditions to be expected during the forecast-period.

Twice weekly the river-forecaster can prepare a forecast on the basis of the regularly issued forecasts of weather. In most cases, however, it will be necessary to go even farther into the future to prepare a potential flood-warning. It is therefore necessary to resort to statistical analysis in making the necessary extension to the forecast which can only provide a safeguard against the abrupt rise of temperature to critical values. In order to demonstrate the method presented the author has utilized the records of temperature and precipitation at Scranton, Pennsylvania, for the month of March for the 31 years between 1910 and 1940.

Forecasts based on normals--At the present time, forecasts of the total volume of runoff to

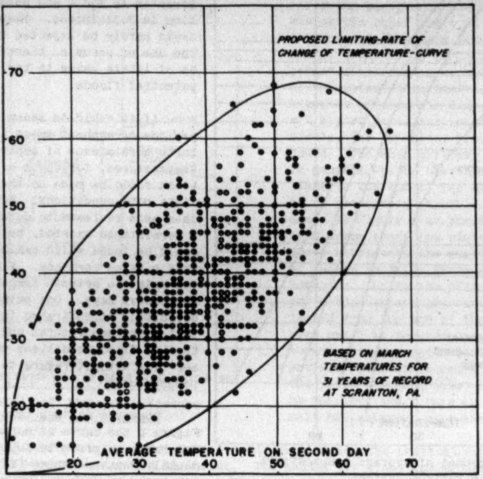


Fig. 1--Relation between average temperatures on successive days

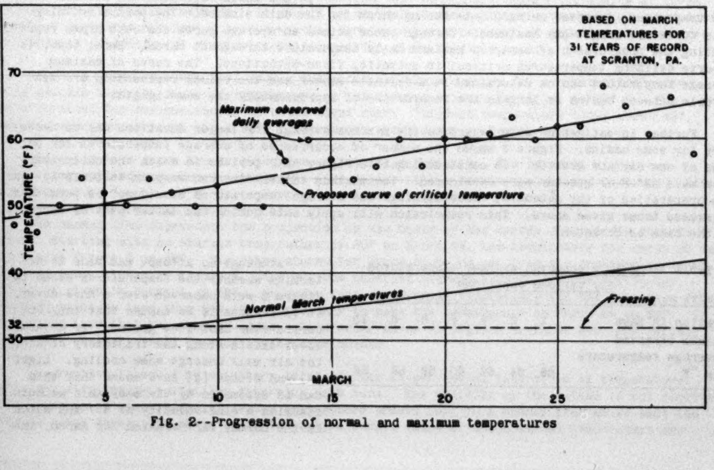


Fig. 2--Progression of normal and maximum temperatures

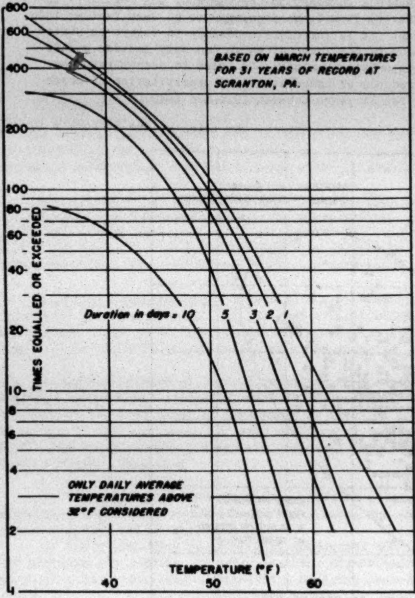


Fig. 3--Occurrences of average temperatures for various periods

be expected from the winter's snowfall are being made for many western river-basins. The procedure used in these forecasts, based principally on comparison with a "normal" year is well known. However, the problem of predicting flood-stages must deal with abnormal conditions rather than with normal ones. The normal monthly temperature for March at Scranton is 37° F and normal precipitation is 3.01 inches. These conditions could hardly be expected to cause floods. The use of normals, therefore, seems to be of little value in the prediction of potential floods.

If it could be shown that there are periods throughout which there is a definite persistence of abnormally high temperatures, forecasts of future conditions could be made on the basis of immediate past conditions. Accordingly the data were reviewed to determine if such a persistence existed, but no relations could be found which exhibited any more than a vague tendency. Figure 1 shows the relation between temperatures on successive days. One point which is definitely demonstrated in the Figure is that high temperatures and therefore potential flood-conditions can occur at any time without regard to the antecedent temperatures.

Observed maximum temperatures--In Figure 2 the curve of normal temperature for March as given in Supplement 25, Monthly Weather Review [2], has been plotted. Above this are plotted the points which represent the maximum average temperature observed on each date during March for the data studied. The points defining this curve are single-day maximums. Through these points an average curve has been drawn representing the progression of observed maximum daily temperature throughout March. Here, then, is a curve defining temperatures critical in potential flood-situations. The curve of maximum average temperature can be determined in a definite manner and the values represented are comparable between basins as long as the records are of approximately the same length.

Further investigation with regard to the maximum average for longer durations may be necessary for some basins. Figure 3 shows the number of occurrences of average temperatures for periods of one day and greater. In constructing this Figure only periods in which the daily averages were 32° F or greater were considered. The maximum values observed were as in Table 1. In the preparation of the potential flood-warnings the average temperatures should not be permitted to exceed those given above. This restriction will apply only during the latter part of March in the case of Scranton.

Table 1--Maximum observed average temperatures for various durations

Duration in days	1	2	3	4	5	6	10
Maximum observed average temperature in °F	68	64	62	60	58	58	56

Although no attempt was made to determine whether the temperatures shown in Figure 2 were observed over a snow-cover, it is reasonable to assume that they occurred over snow-free ground. If a snow-cover exists along the trajectory of air, the air will undergo some cooling. Light [3] and Wilson [4] have shown that this can be estimated by thermodynamic methods. Assuming a wind-velocity of 8.7 mph which is the normal for Scranton for March, the

Table 2--Reduction of air-temperatures in air passing over snow-fields

Distance air travels over snow, miles	Reduction of air-temperature in °F for air originally at	
	55°	60°
50	4	4
100	7	8
200	11	13
300	15	18

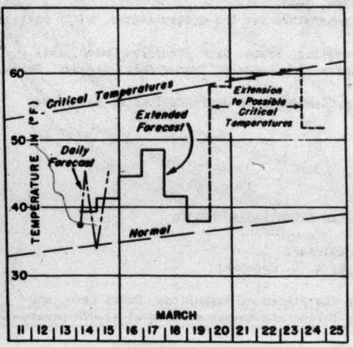


Fig. 4--Example of proposed procedure

amounts of cooling as given in Table 2 would be expected. The forecaster can by means of Table 2 compute the reduction which can be expected to result from a snow-cover along the normal trajectory of air to the basin and apply this reduction to the maximum temperatures of Figure 1.

Observed temperature-changes--In the foregoing paragraphs a method of determining the upper limit of the critical temperatures has been described. It remains, however, to place the critical period with respect to time after the end of the extended forecast of weather. Since a period of moderate temperatures may permit a portion of the snow-cover to melt slowly, the potential flood is thereby reduced. The most critical situation would, in general, place the high temperatures as close to the end of the extended forecast as is reasonably possible. Referring again to Figure 1 an enveloping curve has been drawn about the plotted points. This curve represents the maximum observed rates of change in daily average temperatures at Scranton. Using the rising side of this curve the temperature-curve can be projected from the end of the extended forecast until it reaches the maximum temperature-curve at a rate equal to the observed maximum rates of increase. In this way the temperature-forecast can be extended as far into the future as is necessary to melt the existing snow-cover.

Conclusions--A procedure has been presented for determining the critical conditions under which potential flood-warnings should be issued. The method envisions the projection of temperature into the future for four or five days on the basis of the forecasts issued by the United States Weather Bureau, and extending the prediction into the future beyond the limits of these forecasts by statistical methods. It should be emphasized again that the projection beyond the limits of the forecasts issued by the Weather Bureau is not a forecast of expected temperatures but rather a projection of critical conditions which might possibly occur.

Figure 4 shows an example of such a projected temperature-curve for a hypothetical case. It is assumed that the observed temperature on the morning Friday, March 14, is 37° F. The daily forecast for the succeeding 36 hours might read: "Highest temperature today about 45°, lowest temperature tonight about 34°; tomorrow not much change in temperature."

The solid line shows the extended forecast through March 19. The forecast might read: "Temperature willaverage above normal next five days. Little change tonight and tomorrow. Rising temperature Sunday and Monday. Temperature near normal end of period."

The dashed line represents the projection on the basis of the curves presented with this paper. Starting with an average temperature of 38° on March 19, the temperature for March 20 is taken from Figure 1 as 58°. The temperatures for March 21 to 23 are from the proposed curve of critical temperatures of Figure 2. The maximum observed average temperature for a five-day period is given in Table 1 as 58°. In order that the average temperature for the five days from March 20 to 24 be less than 58° it is necessary to make the temperature on March 24 as 52°. It is assumed here that the snow could be melted under these conditions by March 24. Any further extension, however, would be made in the same manner.

In practice it would be necessary to divide the larger basins into zones of temperature-influence with separate stations governing each zone. The validity of the method is not destroyed if the points of maximum daily average temperature should fall in a manner that would make the average curve horizontal. This would indicate a single value of the critical temperature and would, of course, simplify the operation.

No discussion of the methods of computing the snow-melt from the critical conditions here defined is contemplated. Light [3] and Wilson [4] have outlined methods for the computation of snow-melt on a thermodynamic basis which, with simplifying assumptions, could be applied to the problem. Snyder [5] has presented degree-day curves for the computation of snow-melt in Pennsylvania basins. Reliable information concerning depth, density, and water-content of the snow-mantle are of course necessary.

References

[1] H. C. Willett, The Weather Bureau-Massachusetts Institute of Technology five-day forecasts, Bull. Amer. Met. Soc., v. 21, No. 7, pp. 306-307, 1940.

[2] Supp. 25, Mon. Weath. Rev., Normals of daily temperature for the United States, U. S. Govt. Print. Off., 1925.

[3] Phillip Light, Analysis of high rates of snow-melting, Trans. Amer. Geophys. Union, 1941.

[4] Walter T. Wilson, An outline of the thermodynamics of snow-melt, Trans. Amer. Geophys. Union, 1941.

[5] Report of cooperative hydrologic investigations, Commonwealth of Pennsylvania, pp. 93-94. August, 1939.

U. S. Weather Bureau,
Sacramento, California

HYDROMETEOROLOGY OF THE SAN JUAN RIVER BASIN, MEXICO

Andrés García Quintero
(Presented in abstract by A. L. Cochran)

Introduction--The San Juan River Basin lies in the states of Tamaulipas, Nuevo Leon, and Coahuila in the northeast region of the Republic of Mexico and covers an area of 11,800 square miles.

The Physical, geological, and topographical conditions are favorable in a suitable meteorological situation to the formation of violent storms which cause disastrous floods in the main stream and tributaries.

The region in which this basin is located is similar to the Texas region; in fact, it is an extension of it to the south. Consequently, it is exposed to the same cyclonic disturbances which originate in the Caribbean Sea and enter the Continent either through the coast of Veracruz and Tamaulipas in Mexico or through Texas and other coastal states of the United States.

In order to control the San Juan River regime, the National Irrigation Commission has made special studies and begun the construction of control works to store the waters of the San Juan River in the El Azucar Reservoir situated 19 miles to the southeast of its confluence with the Rio Bravo.

The hydrologic studies made show the following capacities required of the reservoir:

For silt-deposits....................	244,000 acre-feet
For irrigation of 150,000 acres......	568,000 acre-feet
For flood-control....................	893,000 acre-feet
Total capacity......	1,705,000 acre-feet

To establish the minimum capacity for flood-control it has been necessary not only to study the characteristics of the storms which have caused great floods in the past, but also to install and operate a vast network of stations provided with recording gages.

The data obtained were used for the following purposes: (1) To study the relation between the annual rainfall-rates and the runoff; (2) to determine the rainfall-intensities; (3) to ascertain the lag-time of floods; (4) to study the operation of the El Azucar Reservoir before and during storm-periods; and (5) to predict the magnitude of floods.

Storms--The general floods in the San Juan River Basin originate in the saturated humid winds from the Gulf of Mexico; although these rains cause the runoff of the San Juan River in

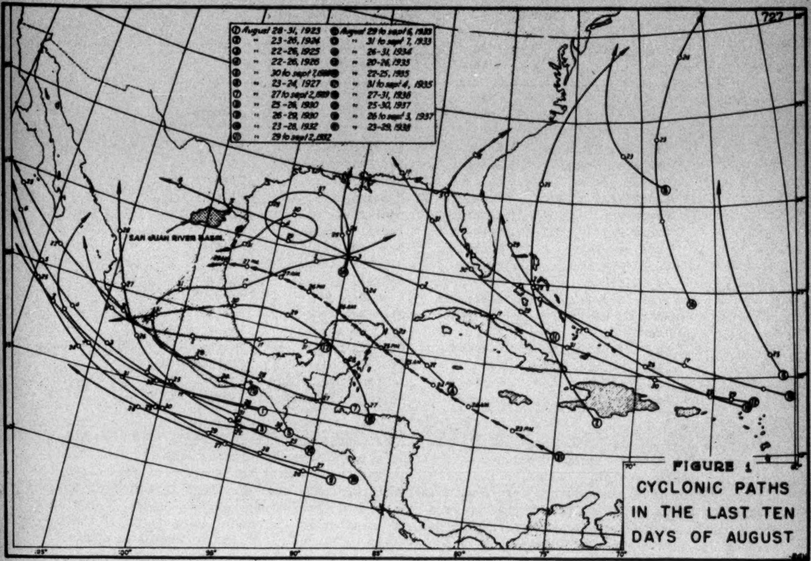

① August 28-31, 1923
② " 23-26, 1924
③ " 22-26, 1925
④ " 22-26, 1926
⑤ " 30 to sept 2, 1926
⑥ " 23-24, 1927
⑦ " 27 to sept 2, 1929
⑧ " 25-26, 1930
⑨ " 26-29, 1930
⑩ " 23-28, 1932
⑪ " 29 to sept 2, 1932
⑫ August 29 to sept 6, 1932
⑬ " 31 to sept 7, 1933
⑭ " 26-31, 1934
⑮ " 20-26, 1935
⑯ " 22-25, 1935
⑰ " 31 to sept 4, 1935
⑱ " 27-31, 1936
⑲ " 25-30, 1937
⑳ " 26 to sept 3, 1937
㉑ " 23-29, 1938
SAN JUAN RIVER BASIN
105°
100°
95°
90°
85°
80°
75°
70°
65°
60°

FIGURE 1
CYCLONIC PATHS IN THE LAST TEN DAYS OF AUGUST

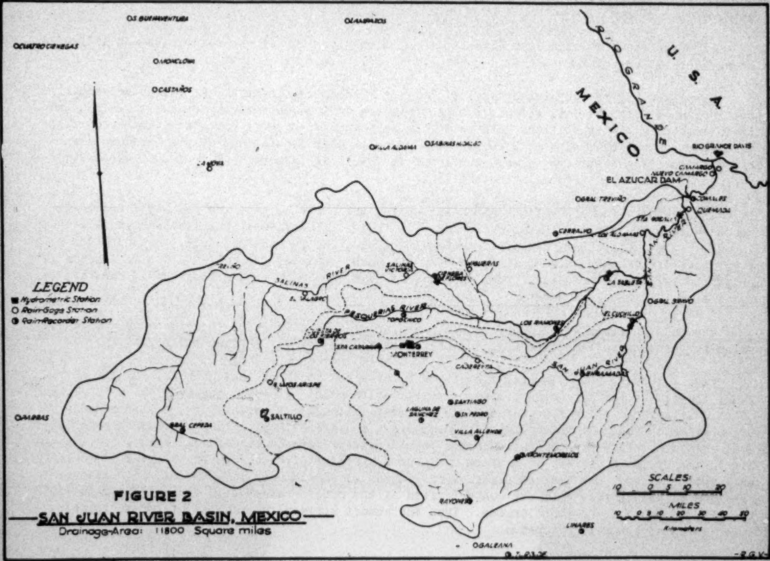

U. S. A.
MEXICO
RIO GRANDE
RIO GRANDE DAMS
CAMARGO
NUEVO CAMARGO
EL AZUCAR DAM
GRAL TREVIÑO
COMALES
QUEMADA
STA GERTRUDIS
CERRALVO
LOS ALDAMAS
SAN JUAN RIVER
LA BARRETA
GRAL BRAVO
EL CUCHILLO
LOS RAMONES
HIGUERAS
CIENEGA DE FLORES
SALINAS VICTORIA
SALINAS RIVER
PESQUERIAS RIVER
TOPOCHICO
MONTERREY
STA CATARINA
CADEREYTA
SANTIAGO
SN PEDRO
LAGUNA DE SANCHEZ
VILLA ALLENDE
MONTEMORELOS
RAYONES
LINARES
GALEANA
SALTILLO
RAMOS ARIZPE
GRAL CEPEDA
PARRAS
CUATRO CIENEGAS
S. BUENAVENTURA
MONCLOVA
CASTAÑOS
LAMPAZOS
VILLA ALDAMA
SABINAS HIDALGO
CANDELA
LA NOVIA
LEGEND
■ Hydrometric Station
○ Rain-Gage Station
◑ Rain-Recorder Station
SCALES:
10 0 5 10 20
MILES
10 0 5 10 20 30 40 50
Kilometers
R.G.V.

FIGURE 2

SAN JUAN RIVER BASIN, MEXICO

Drainage-Area: 11800 Square miles

Table 1--Rain-recorders in operation in and near the San Juan River Basin

Name	Kind of recorder	Name	Kind of recorder
Allende, N.L.	Friez	Linares, N.L.	Fuess
Barretal, Tamps.	Stevens L.	Los Ramones	Stevens L.
Burgos, Tamps.	Stevens A.	Mendez, Tamps.	Stevens A.
Cadereyta, N.L.	Fuess	Montemorelos	Friez
Cerralvo, N.L.	Lambrecht	Monterrey, N.L.	Friez
C. de Flores, N.L.	Stevens A.	Padilla, Tamps.	Fuess
Comales, Tamps.	Fuess	Rayones, N.L.	Friez
C. de Fierros	Fuess	Reynosa, Tamps.	Fuess
El Cuchillo	Stevens A.	Saltillo, Coah.	Lambrecht
Gral. Cepeda.	Stevens A.	S. Fernando	Stevens L.
Hda. S. Pedro	Stevens A.	Sta. Catarina	Fuess
Iturbide, N.L.	Fuess	Sta. Gertrudis	Lambrecht
La Tableta, N.L.	Stevens A.	Cd. Victoria	Stevens A.
Lag. Sanchez, N.L.	Friez	Topo Chico	Stevens A.
Las Comitas, N.L.	Fuess	V. Santiago, N.L.	Friez
Las Enramadas	Lambrecht	Villagran, Tamps.	Stevens L.

normal years, they are unimportant compared to the extraordinary storms caused by cyclonic disturbances that with a regular frequency enter the continent through Veracruz, Tamaulipas, Texas, and other coastal states. These cyclones originate in the Caribbean Sea and follow well-defined courses moving from southeast to northwest. The most favorable time for these disturbances includes the months of August and September (see Fig. 1) and the intense rains along the course of the disturbance cause enormous surface-runoff which is often greater than the capacity of the streams and rivers draining the region. Thus the vast agricultural fields in the lowland margins of the rivers are flooded and therefore cannot be cultivated because appropriate water-control is lacking.

Figure 2 shows the San Juan River Basin with the location of the rain-gages and active hydrometric stations.

Operation of the Hydrometeorological Service--The operation of the El Azucar Reservoir is being planned with the data which are being obtained by the Hydrometric Service. Besides the installation of gaging stations with recording apparatus, hydrometric stations are being built to complete a network which will enable studies to be made of each one of the San Juan River tributaries. These streams, as was mentioned in the first part of this report, cover extensive regions of different hydrological conditions.

The installation of stations was begun during the first part of the year 1938 and it includes German and North American recorders. In Table 1 is a list of the stations installed up to date. Their efficiency was tried during August 26, 27, 28, and 29, 1938, in connection with a cyclonic disturbance which originated over the Caribbean Sea; the only cyclone of comparable proportions occurred practically during the same days and month in the year 1909. However, the cyclone of 1938 was less severe.

The data obtained in or near the Basin are presented in Table 2; these data were of great value for they found immediate application in the studies made for flood-control.

Figure 3 shows the isohyetal map of the rains which occurred on August 27, 28, and 29, 1938; it will be readily noted that only a part of the Basin (Zone A) received the most violent rains. This zone is limited on the south and west by the great heights of the Sierra Madre Oriental which reach in some ranges to 13,000 feet above sea-level. Thus geographical and topographical conditions are favorable to the development of intense convection because the humid air in the cyclonic current upon being deviated upward rapidly cools to produce the instability and precipitation. Besides, this region has marked slopes in both longitudinal and traverse directions which contribute to the concentration of the runoff rather than to the regulation of the flow in canyons and other drains. Thus the runoff strikes the flatter hill country of the lower basin with terrible impetus.

In the lower basin formed by the same rolling country as the Texas Region the River over-

Table 2--Daily rainfall during the cyclonic storms of August, 1938

Rain-gage at	August, 1938				
	26	27	28	29	Total
	mm	mm	mm	mm	mm
COAHUILA					
Gral. Cepeda	0.0	6.5	50.5	0.0	57.0
Monclova	0.0	0.0	50.0	49.2	99.2
Ramos Arizpe	0.0	5.5	69.0	1.5	76.0
Saltillo	2.0	0.6	52.0	2.5	57.1
Santa Teresa	0.0	0.0	1.0	15.5	16.5
NUEVO LEON					
Cadereyta	0.0	27.6	....	66.9	.....
Cienega de Flores	0.0	9.4	83.0	24.5	116.9
El Cuchillo	0.0	3.7	90.1	1.7	95.5
Gral. Bravo	0.0	0.0	165.0	0.0	165.0
Higueras	0.0	17.5	78.0	75.0	170.5
Las Enramadas	0.0	20.0	121.0	10.0	151.0
Linares	0.5	24.3	245.0	61.0	330.8
Montemorelos	0.0	21.4	264.9	35.2	321.5
Monterrey	0.0	7.1	291.5	35.4	334.0
Rayones	0.0	31.9	175.6	40.7	248.2
Santiago	...	28.7	263.3	9.7	.....
Santa Catarina	0.0	19.8	193.0	2.0	214.8
Zaragoza	0.0	35.0	173.5	150.0	358.5
TAMAULIPAS					
Abasolo	0.0	83.5	128.2	0.0	211.7
Aldama	43.5	5.0	0.0	0.0	48.5
Burgos	0.0	29.0	300.0	0.0	329.0
C. Comales	0.0	10.6	102.0	0.0	112.6
C. Guerrero	0.0	15.0	72.0	0.0	87.0
Hidalgo	0.0	23.5	125.5	228.0	377.0
Jerez	27.5	12.5	61.0	0.0	101.0
La Barra	0.0	35.0	4.0	0.0	39.0
Mante	4.0	13.2	176.9	44.5	238.6
Matamoros	0.0	53.8	36.0	0.0	89.8
San Carlos	0.0	120.0	180.0	0.0	300.0
San Fernando	0.0	....	26.0	0.0	.....
Santa Elena	5.0	2.2	175.0	48.0	230.2
Soto La Marina	7.0	....	....	....	.....
Tampico	0.0	17.0	5.7	0.0	22.7
Tomatlan	4.0	43.0	190.0	300.0	637.0
SAN LUIS POTOSI					
Col. A. Obregon	0.5	2.3	17.0	4.9	24.7
Charcas	0.0	0.0	3.6	15.0	18.6
El Meco	18.7	0.6	98.8	61.3	179.4
Matehuala	0.0	0.0	0.0	31.2	31.2
Penitas	18.3	1.3	54.0	15.7	89.3
Presa Obregon	2.5	0.0	11.7	11.0	25.2
Rio Verde	0.0	0.0	3.0	10.0	13.0
San Luis Potosi	0.0	0.0	20.0	22.0	42.0
San Antonio	0.0	0.0	0.0	0.0	0.0
Tantizohuiche	2.9	0.0	5.1	4.4	12.4
Villa Arriaga	0.0	0.0	21.0	27.5	48.5
VERACRUZ					
Ozuluama	0.0	0.0	0.0	0.0	0.0
Tuxpan	0.0	0.0	0.0	7.5	7.5

flows; and its partial regulation does not prevent further overflows. When the Rio Grande into which the San Juan River enters near Rio Grande Davis, Texas, is also in flood, its backwater added to the flood-flow of the San Juan River creates even more critical conditions.

Rain-intensity--Rain-intensity in the San Juan River Basin had not been studied because there were no recording apparatus available to obtain such data. The only rain-gage stations existing before 1938 made observations once a day and very few of the observers made any additional notations during great storms.

The data taken of the cyclone of August, 1938, made it possible to deduce the rain-intensities shown in Tables 3 and 4.

Rain-distribution--Besides the topographical distribution, the rainfall was studied by the mass-curves shown in Figure 4. The graphs were formed by accumulating the percentages of total

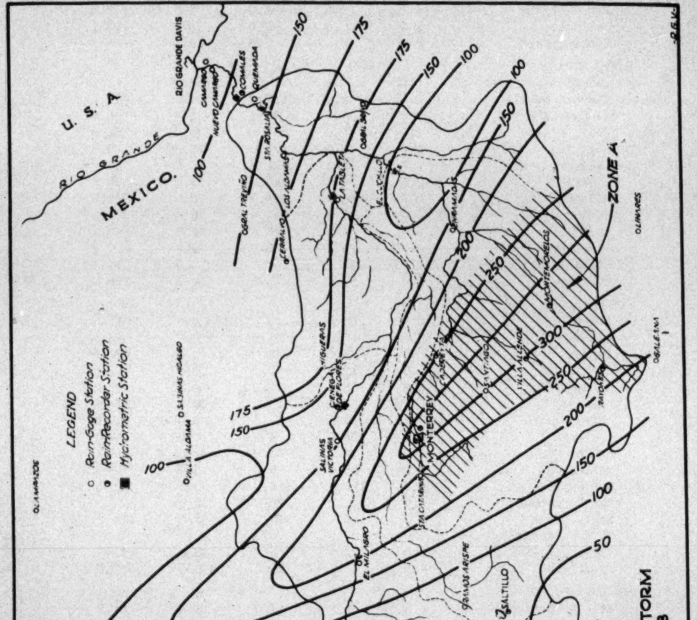

U. S. A.
MEXICO.
RIO GRANDE
RIO GRANDE DAVIS
ZONE A
LEGEND
Rain-Gage Station
Rain-Recorder Station
Hydrometric Station
MONTERREY
SALTILLO
SALINAS VICTORIA
EL MILAGRO
RAMOS ARISPE
STA. CATARINA
CADEREYTA
VILLA ALLENDE
MONTEMORELOS
RAYONES
GENERAL CEPEDA
CERRALVO
LOS ALDAMAS
STA. ROSALIA
LA TABLETA
CAMARGO
NUEVO CAMARGO
COMALES
QUEMADA
CIENEGA DE FLORES
HIGUERAS
SALINAS HIDALGO
VILLA ALDAMA
LAMPAZOS
MONCLOVA
CASTAÑOS
LA JOYA
LINARES
SCALE
KILOMETERS
0 5 10 20 30 40 50 100
50
100
150
175
200
250
300

FIGURE 3
ISOHYETAL MAP OF THREE-DAY STORM
AUGUST, 27 th, 28 th and 29 th, 1938
IN MILLIMETERS

rainfall, hour by hour. These curves were very helpful in the studies relating to probable floods.

Concentration-time--For the studies on flood-control it is fundamental to have créditable data on concentration-time, that is, the period from the time the storm began to the time the flood-flow reached its maximum discharge. To obtain these data mass-curves of the rainfall were drawn on the same time-scale as the hydrographs of the flood-flows; these are shown by the graphs in Figure 5.

Predicting flood-flows--Using data similar to those in Figure 5 the lag-time of flood-flows caused by storms located in different parts of the watershed will be studied. For this strategically located pluviographic stations will be chosen, the available data in each portion of the watershed will be considered, and thus in accord with these data the flood-flows entering the Reservoir will be determined.

Flood-control--The hydrometeorological studies made for flood-control were divided into: (1) Estimation of the maximum probable storms; (2) estimation of the maximum probable floods with relation to the maximum probable storms; and (3) operation of the El Azucar Reservoir.

(1) To estimate the maximum probable storms in the San Juan River Basin the following studies were made:

(a) To determine the relation of the mean rainfall in the Basin during the three-day storm-period to the rainfall observed in the same three days at one station located within the watershed; its data were applied to the relation-graph to show the average rainfall in the Basin. After studying various stations, Monterrey, N.L., was chosen as representative.

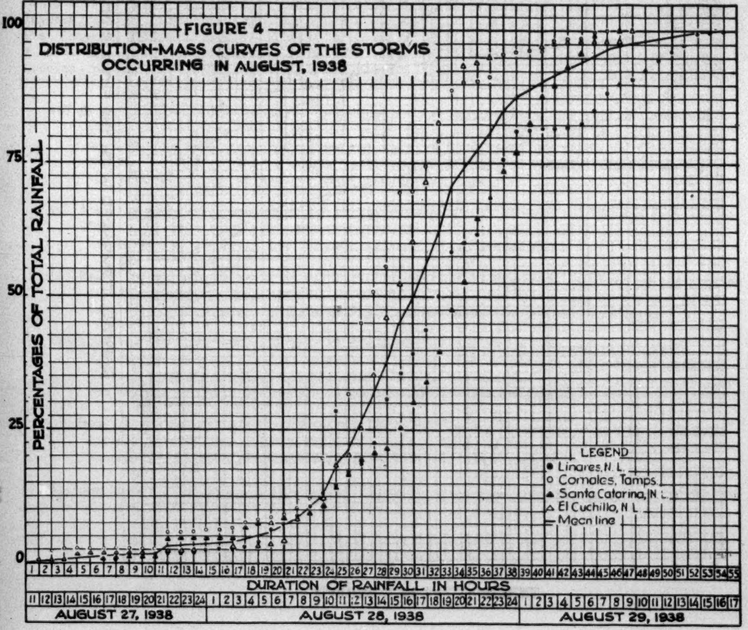


FIGURE 4

DISTRIBUTION-MASS CURVES OF THE STORMS OCCURRING IN AUGUST, 1938

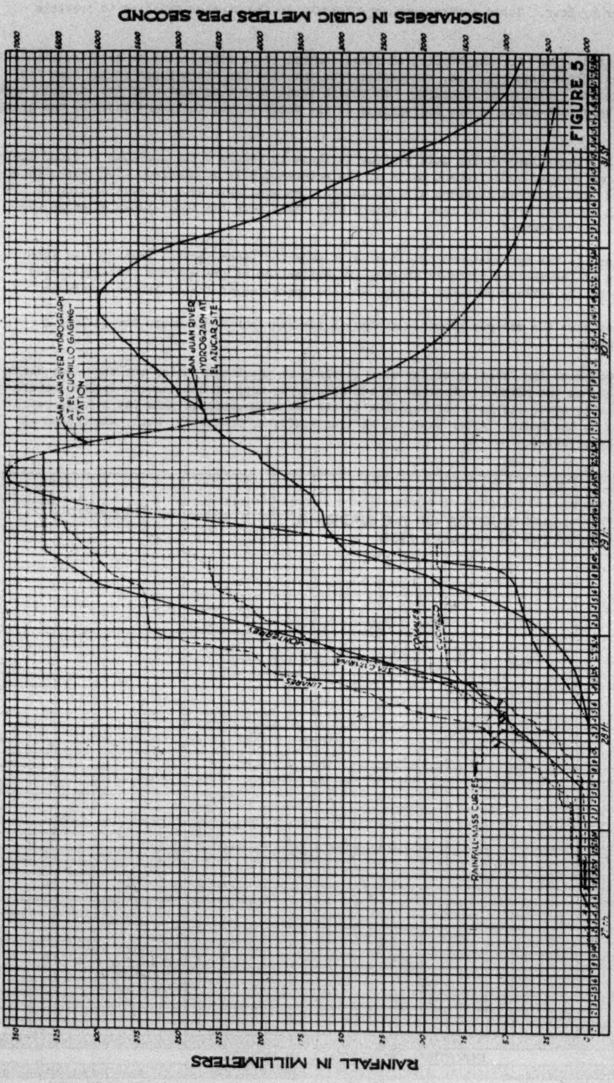


FIGURE 5

RAINFALL COMPARED WITH THE FLOODS PRODUCED-AUGUST 1938

Table 3--Intense rainfall in short intervals of time during the cyclonic storms of August, 1938

Rain-recorder station	Date	Intervals of time in minutes									
		5	10	15	20	30	45	60	80	100	120
		mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
Cadereyta	Aug. 28	7.6	10.0	17.5	21.3	24.5	28.5	28.9	30.3	30.8	31.2
C. de Flores, N.L.	Aug. 28	3.8	5.2	5.6	6.6	7.8	8.9	9.5	12.0	14.6	18.6
El Cuchillo, N.L.	Aug. 28	5.5	6.7	8.7	9.2	10.0	12.2	13.3	16.2	18.5	20.1
Linares, N.L.	Aug. 28	9.7	14.7	15.2	17.6	21.1	29.7	39.5	43.7	46.0	48.8
Montemorelos, N.L.	Aug. 27	4.7	4.8	5.7	6.8	8.5	10.0	10.0	10.0	10.0	10.0
Rayones, N.L.	Aug. 27	2.1	3.3	4.4	5.0	5.8	6.9	8.4	10.0	11.2	12.8
Sta. Catarina, N.L.	Aug. 28	4.0	5.5	9.5	10.0	14.7	20.0	26.0	33.0	37.3	40.0
Santiago, N.L.	Aug. 27	4.1	5.1	6.7	10.4	12.5	14.6	15.7	17.0	17.5	17.7
Comales, Tamps.	Aug. 28	5.0	7.2	9.0	10.0	13.5	16.2	17.7	20.5	21.4	22.0

Table 4--Rainfall-intensities observed in the cyclonic storms of August, 1938, reduced to millimeters per hour

Rain-recorder station	Date	Intervals of time in minutes									
		5	10	15	20	30	45	60	80	100	120
Cadereyta, N.L.	Aug. 28	91.2	60.0	70.0	63.9	49.0	38.0	28.9	22.7	18.5	15.6
C. de Flores, N.L.	Aug. 28	45.6	31.2	22.4	19.8	15.6	11.8	9.5	9.0	8.8	9.3
El Cuchillo, N.L.	Aug. 28	66.0	40.2	34.8	27.6	20.0	16.2	13.3	12.2	11.1	10.1
Linares, N.L.	Aug. 28	116.4	88.2	60.8	52.8	42.2	39.5	39.5	32.8	27.6	24.4
Montemorelos, N.L.	Aug. 27	56.4	28.8	22.8	20.4	17.0	13.3	10.0	7.5	6.0	5.0
Rayones, N.L.	Aug. 28	25.2	19.8	17.6	15.0	11.6	9.2	8.4	7.5	6.7	6.4
Sta. Catarina, N.L.	Aug. 28	48.0	33.0	38.0	30.0	29.4	26.6	26.0	24.8	22.4	20.0
V. Santiago, N.L.	Aug. 27	49.2	30.6	26.8	31.2	25.0	19.4	15.7	12.8	10.5	8.9
Comales, Tamps.	Aug. 28	60.0	43.2	36.0	30.0	27.0	21.5	17.7	15.4	12.8	11.0

(b) By application of the probability methods to the maximum three-day rainfall observed yearly at Monterrey since 1898, the total three-day rainfall-rates were obtained not only for the different frequencies but also for the conditions resulting from transposing the Basin in such a manner as to obtain the maximum average rainfall during the cyclonic storms of August, 1909, and August, 1938.

(c) Applying the data obtained in (b) to the relation-graph between the average rain in the Basin and the rainfall in Monterrey given by (a), the average three-day rainfall in the Basin for the different frequencies studied was determined.

(d) Using the mean percentages of rainfall-distribution of Figure 4, observed in the cyclone of 1938, the daily mean rainfall in the Basin during the three days of maximum rainfall for the conditions considered was obtained using the probability-method.

(e) Applying the distribution-graphs to the daily average rains observed in the unit-hydrographs for the San Juan River at El Azucar, the respective pluviographs were deduced. Reducing these pluviographs by means of the maximum observed flood-coefficient, the maximum probable hydrographs were deduced for each frequency.

(f) Routing the resulting hydrographs through the El Azucar Reservoir with a spillway provided with nine Stoney gates for a maximum discharge of 795,000 second-feet, several alternative reservoir-operation plans were studied and compared.

Maximum observed and probable discharges--In Table 5 are included all the maximum discharges observed and also those estimated by the hydrometeorological studies.

Table 5--Maximum observed and probable discharges of the San Juan River at El Azucar, Tamaulipas, Mexico

Date	Discharge, second-feet	Date	Discharge, second-feet
August 30, 1909	318,000	September, 1932	187,000
June, 1924	27,600	September, 1933	136,300
September, 1925	44,200	October, 1934	13,700
October, 1926	34,900	September, 1935	29,000
June, 1927	44,800	July, 1936	51,600
September, 1928	20,000	October, 1937	9,600
September, 1929	8,940	August 30, 1938	233,000
October, 1930	32,300	September, 1939	65,000
January, 1931	12,400		

Probable mean frequency and discharge

Mean frequency	Discharge, second-feet
One in 100 years	269,000
One in 500 years	413,000
One in 1,000 years	465,000
One in 10,000 years	672,000

Comision Nacional de Irrigacion,
Mexico City, Mexico

THE EFFECT OF A WELL ON THE FLOW OF A NEARBY STREAM

C. V. Theis

In many irrigation-districts where the supplies of surface-water from a stream have been entirely appropriated, pumping from wells has been resorted to in order to supplement the surface-supply. Where the pumps are near a stream that has a flow during the irrigation-season, either because of normal ground-water flow or because of return flow from surface-water irrigation, the pumping is likely to diminish the stream-flow. Conversely, diversions of water from a stream may diminish the supply of wells that were formerly supplied indirectly by seepage from the stream, but the problem involved is of a different nature than its converse and will not be discussed here.

Theoretically, it would be possible to determine the decrease in stream-flow by a comparison of the position of the water-table before and after pumping and by a determination of the transmissibility of the aquifer. However, in most places where the problem is important, study is begun only after pumping has been in progress, and generally there is no accurate knowledge of the position of the water-table in the period preceding pumping. Moreover, such records as do exist cannot usually be used for comparison because the water-table has reacted to many influences other than the pumping, such as variations in the natural recharge, amount of irrigation-water applied, and the stage of the stream into which the ground-water discharges. Further, comparisons of actual stream-flow before and after pumping are not generally of critical value because the flow of a stream from year to year depends on many extraneous factors. There is, accordingly, need of an approach to the problem more or less independent of these factors.

The water pumped from wells in a stream-valley must be balanced in amount by a reduction in ground-water storage, by an increase in the recharge, by a reduction in the amount of transpiration from vegetation and of evaporation in areas where the water-table is near the surface, by a reduction of ground-water discharge into the stream, or by a combination of these. The following discussion arrives at a criterion for estimating the proportion of the water pumped by a well represented by a decrease in stream-flow, the possible reduction in transpiration by native vegetation and the possible increase in recharge being neglected.

In this discussion, certain idealizations of the hydraulic system are made in order to simplify the problem sufficiently to make it amenable to mathematical treatment. The aquifer is considered homogeneous and isotropic. It is assumed that the transmissibility of the aquifer is constant. This assumption introduces an error which increases with the ratio between the amount

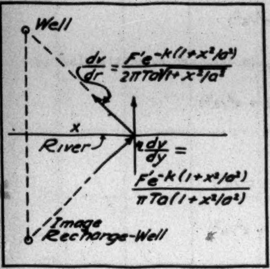

Well
$\frac{dv}{dr} = \frac{F'e^{-k(1+x^2/a^2)}}{2\pi Ta\sqrt{1+x^2/a^2}}$
x
River
$\frac{dy}{dy} =$
$\frac{F'e^{-k(1+x^2/a^2)}}{\pi Ta(1+x^2/a^2)}$
Image
Recharge-Well

Fig. 1--Ground-water gradient at a stream in vicinity of a pumped well

of lowering of the water-table and the saturated thickness of the aquifer, and therefore restricts the use of the results to aquifers of some thickness, such as comparatively deep alluvial fill in stream-valleys. The slope of the water-table or of the floor underlying the aquifer has no significance within the limits that the assumption of constant transmissibility holds. Hence, although for brevity, the flux "from the river" will be spoken of in the following treatment, the flux may be either an actual movement of water from the river or a decrease of the customary movement of water to the river. Several other assumptions in the basic non-equilibrium formula have been discussed previously [C. V. Theis, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage, Trans. Amer. Geophys. Union, pp. 521-524, 1935]. They do not seem to have practical application to the present problem. For the present problem, the course of the river is idealized as a straight line. The practical significance of this assumption is discussed below. It is further assumed that the ground-water is in free communication with the stream, that is, the stream-bed is not so heavily silted that the resistance to movement into or out of the stream is a significant part of the resistance to the ground-water flow; that the movement of the ground-water can be reversed, that is, for instance, that the ground-water does not discharge as springs above the level of the river; and that the stream maintains a flow past the pumped area. These latter assumptions are included in a general assumption that the ground-water head at the stream does not change significantly because of the pumping.

The equation for the discharge of a well in an aquifer of infinite areal extent is given by Theis (loc. cit., p. 520].

$$v = (114.6\ F/T) \int_{1.87\ r^2 s/Tt}^{\infty} (e^{-u}/u)\ du$$

in which v is the lowering of the water-table at any place and time, in feet; F is the discharge of the well in gallons a minute; T is the coefficient of transmissibility; r is the distance from the well to the point of observation, in feet; s is the coefficient of storage, or specific yield; and t is time since the discharge began, in days.

For our purpose it will be convenient to consider the flux of the well in gallons a day in order to make it comparable to the customary units of T.

$$F' = 1440\ F$$

and

$$v = (F'/4\pi T) \int_{1.87\ r^2 s/Tt}^{\infty} (e^{-u}/u)\ du$$

The derivative of this with respect to r is

$$(dv/dr) = (F'/2\pi Tr)\ e^{-1.87\ r^2 s/Tt}$$

Consider conditions around a well a distance a from a river idealized as a straight line of infinite extent (Fig. 1). If the ground-water head at the stream does not change, the conditions may be expressed by adding a hypotehtical image recharge-well to the system a distance a on the other side of the straight line. At a distance x along the river, measured from the perpendicular joining the wells, the hydraulic gradient caused by the real well will be

$$(dv/dr) = (F'/2\pi T\ \sqrt{a^2 + x^2})\ e^{-1.87\ (a^2 + x^2)\ s/Tt}$$

The hypotehtical image-well will produce a hydraulic gradient similar in amount at the point x. By vectorial addition of the two gradients the resultant gradient directed perpendicularly from the river will be

$$(dv/dy) = (2F'/2\pi T\ \sqrt{a^2 + x^2})\ (a/\ \sqrt{a^2 + x^2})\ e^{-1.87\ (a^2 + x^2) s/Tt}$$

$$= [F'a/\pi T(a^2 + x^2)]\ e^{-1.87\ (a^2 + x^2) s/Tt}$$

For simplification, write $k = 1.87\ a^2 s/Tt$.

$$(dv/dy) = [F'/\pi Ta\ (1 + x^2/a^2)]\ e^{-k\ (1 + x^2/a^2)}$$

The flux away from the river, F_r, in any linear interval, dx, is obtained by multiplying the gradient by the transmissibility.

$$(dF_r/dx) = T(dv/dy) = [F'/a(1 + x^2/a^2)]\ e^{-k\ (1 + x^2/a^2)}$$

The total flux away from the river is

$$F_r = (F'/\pi a)\int_0^\infty [e^{-k\ (1 + x^2/a^2)}\ dx]/(1 + x^2/a^2)$$

$$= (2F'/\pi a)\int_0^\infty [e^{-k\ (1 + x^2/a^2)}\ dx]/(1 + x^2/a^2)$$

The ratio, P, between the flux from the river and that from the pump is

$$P = (F_r/F') = (2/\pi a)\int_0^\infty [e^{-k\ (1 + x^2/a^2)}\ dx]/(1 + x^2/a^2)$$

writing $z = (x/a)$

$$P = (2/\pi)\int_0^\infty e^{-k\ (1 + z^2)} dz/(1 + z^2)$$

and [de Han, Bierens, Nouvelles Tables d'Integrales de finies, Table 91, No. 13, p. 133, Stechert and Co., New York City, 1939]

$$P = 1 - \left(\frac{2e^{-k/2}}{\sqrt{\pi}}\right) \sqrt{\sum_1^\infty \frac{k^n}{n!} \sum_1^n \frac{(-1)^{m-1}}{2m-1}}$$

$$= 1 - e^{-k/2}\ (1.273239k + 0.424413k^2 + 0.183912k^3 + 0.038399k^4$$

$$+ 0.008859k^5 + 0.001316k^6 + 0.000207k^7 + 0.000024k^8 + \ldots)^{1/2}$$

This series converges rapidly for fractional values of k. For larger values of k the integral can be more easily evaluated graphically or by Simpson's rule in the following form: Let $z = \tan u$, then $dz = \sec^2 u\ du$, and $(1 + z^2) = (1 + \tan^2 u) = \sec^2 u$. Changing the limits of integration

$$P = (2/\pi)\int_0^{\pi/2} e^{-k\ \sec^2 u}\ du$$

Figure 2 gives values of P for various values of k and shows therefore the proportion of the pumped water represented by a decrease in the stream-flow according to the assumptions made. As other possible processes that might balance the pump-discharge are neglected, (1 - P) represents the part of the pumped water taken from underground storage.

It can be shown from the last integral that over half the total flux from the river is always derived between points a distance a upstream from the well and the same distance downstream. The proportions derived at greater distances from the pump rapidly diminish with distance. Hence, if the actual river retains an approximately straight course for a distance equal to from two to four times the distance of the pump from the river the method will yield the approximate proportion of water abstracted from the river.

To the extent that the lowering of the water-table permits additional recharge to enter the aquifer or reduces the amount of transpiration from the aquifer, the actual reduction in flow of the stream will be significantly smaller than that indicated by this method. These factors, of course, require individual evaluation in individual areas of pumping.

The equation given indicates that, if there is no significant increase in recharge or decrease in transpiration, the proportion of water taken from stream-flow varies widely depending chiefly on the transmissibility of the aquifer and the distance of the well from the stream. For instance, in an aquifer with a specific yield of 20 per cent and a coefficient of transmissibility of 50,000 (near the lower limit of this coefficient for productive non-artesian aquifers), a well one mile from a stream will take about 30 per cent of its water from stream-flow after one year of pumping and about 90 per cent after 20 years of pumping. A well five miles from the stream will take about two per cent of its water from the stream after five years of pumping and about 20 per cent after 20 years. On the other hand, in an aquifer with a transmissibility of 400,000 (near the upper limit of this coefficient) a well one mile from the river will take about 90 per cent of its water from the stream in three years, and a well five miles from the stream will take about five per cent after one year and about 75 per cent after 20 years of pumping.

U. S. Geological Survey,
Albuquerque, New Mexico

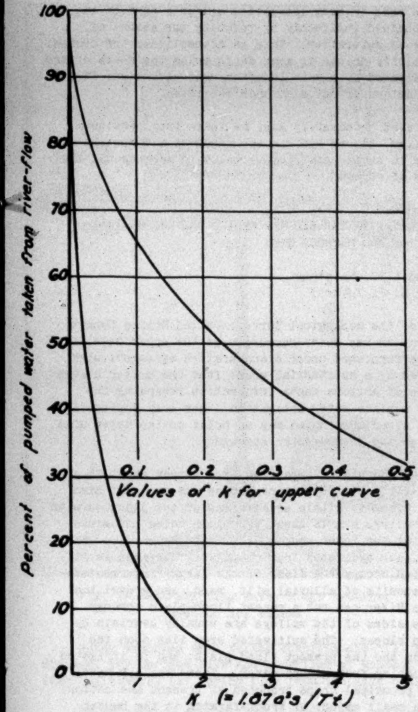


Fig. 2--Values of P for various values of k

DISCUSSION

L. K. WENZEL (U. S. Geological Survey, Washington, D. C.)--The paper by Dr. Theis on the effect of a well on the flow of a nearby stream is an excellent illustration of the adaptability to ground-water problems of the well-discharge formula first introduced by him in 1935 and published in the Transactions of the American Geophysical Union of that year. Most writers on the motion of ground-water have confined their studies to the steady-state flow and, therefore, have developed formulas that apply only to the ultimate condition of the hydraulic system. Since this ultimate condition, or steady-state flow of ground-water, is almost never reached except approximately in localized regions of an aquifer, the application of formulas based on this concept has been very limited and has sometimes given erroneous results. The introduction of the formula for non-steady flow of ground-water, which contains a factor for time, has resulted in the development of many new methods of attack on ground-water problems, including methods for determining coefficients of permeability and coefficients of storage of water-bearing formations, methods for forecasting the amount and rate of decline of the ground-water levels caused by the discharge of wells under specified conditions of operation, methods for predicting the effect on ground-water levels of new or additional well-developments, and now, as given in Dr. Theis's paper, a method for determining the effect of a well on the flow of a nearby stream.

The results obtained by the use of the mathematical approach to ground-water problems, although definitely remunerative, have clearly demonstrated that formulas involving ground-water flow can be applied to field-conditions with assurance only when considerable caution and judgment are exercised. The effects of many factors that influence ground-water flow have not yet been evaluated quantitatively and hence different methods of application must usually be devised to fit conditions in the specific area under investigation.

For the application of the method described by Dr. Theis probably the most important field-factor that must be evaluated is the quantity of ground-water that is used by plants in the area that is affected by the pumping. It is possible that in some localities all or a part of the water removed from the well by pumping may be obtained indirectly by reducing the amount of water that is transpired by plants from the zone of saturation. This is accomplished, of course, through the lowering of the water-table and capillary fringe to some depth below the roots of the plants. Since the quantity of ground-water dissipated by plants is often underestimated, it is important that the effect of this factor on the method is not also underestimated.

Despite the special conditions and factors that necessarily must be taken into consideration in the areas where this method will be applied, the method, in the hands of a competent ground-water hydrologist, will undoubtedly prove to be of considerable value in working out the relation between pumpage from wells and the flow of streams.

GROUND-WATER INVENTORY IN THE UPPER GILA RIVER VALLEY, NEW MEXICO AND ARIZONA: SCOPE OF INVESTIGATION AND METHODS USED

S. F. Turner and L. C. Halpenny
(Presented by S. F. Turner)

Introduction--The Division of Ground Water of the Geological Survey, United States Department of the Interior, has been making an inventory of the water-resources of the upper Gila River since January 1, 1940. Funds for the project are furnished under a cooperative agreement with the Arizona State Water Commissioner, supplemented by a substantial grant from the United States Engineer Office of the War Department. The State of Arizona wants information regarding the quantity of ground-water available to supplement surface-water irrigation. The Army Engineers would like to know the effect that flood-control structures which may be built on the upper Gila will have on existing relations between river-flow and ground-water storage.

The areas being studied are two valleys along the River, separated by a canyon about 25 miles in length. The upper of these, the Duncan-Virden Valley, starts below the mouth of Blue Creek, in New Mexico, and extends along the Gila River to within seven miles of the junction with the San Francisco River. The lower, or Safford Valley, starts about two miles below the mouth of Bonita Creek and extends to the Coolidge Dam, at the lower end of San Carlos Reservoir. This paper considers only the inner valleys that have been excavated from relatively impermeable Pliocene and early Pleistocene lake-bed deposits which occupy the floor of the larger intermontane valleys. These inner valleys are underlain by deposits of alluvial silt, sand, and gravel that yield large quantities of ground-water. The Gila River has cut a recent flood-plain through this alluvial fill. The lake-bed deposits at the sides of the valleys are usually overlain by gravels washed down from the neighboring mountain slopes. The cultivated area lies upon the alluvial fill between the gravel-covered lake-beds and the present flood-plain, and is irrigated by diverting from the flow of the river and by pumping from ground-water. These valleys have been under cultivation since about 1870, and the principal crops produced at present are cotton, alfalfa, small grains, and corn, in addition to a small amount of truck-farming in the Duncan-Virden Valley.

The Safford Valley has been studied several times with a view to further development of water-resources of the eastern part of Arizona, particularly with reference to the San Carlos Irrigation Project. The Surface-Water Division of the Geological Survey has published records of stream-flow in the area for many years [see 1 of "References" at end of paper] and the Ground-Water Division has published two Water-Supply Papers on a part of the area [2,3].

Factors involved--The writers believed it would be necessary to undertake a complete inventory of the water-resources of each valley as the ground-water is influenced by several conflicting factors: Water for irrigation is diverted from the river-flow and pumped from the ground-water supply; the ground-water reservoirs are lowered by transpiration of river-bottom phreatophytes; and the reservoirs in turn lose to the river by influent seepage and gain from the river by effluent seepage. Recharge to the ground-water supply may occur in several other ways.

A tentative water-equation was set up for each valley and methods were applied to evaluate each factor of the equation. Since the valleys are relatively water-tight, the water entering should be equal to the water leaving, plus or minus changes in ground-water storage. An inventory of the water in the entire trough between the mountain ranges was considered too extensive, and therefore the region studied is the inner valley that was excavated in the lake-bed deposits, bounded at each end by river-gaging stations maintained by the Surface-Water Division of the Geological Survey. The geology of the entire trough between the mountain ranges is being mapped, however.

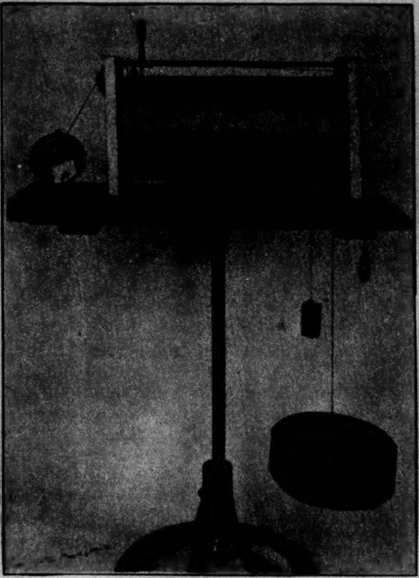


Fig. 1--Self-starting water-stage recorder used on dry washes

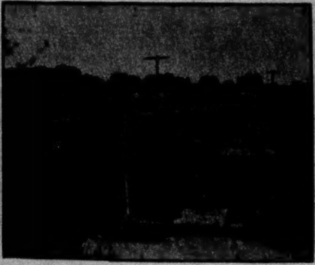


Fig. 2--Typical temporary recorder-structure on normally dry wash

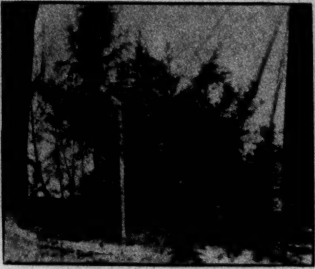


Fig. 3--Tamarisk-growth in tank at Safford Experiment Station near end of 1940 growing-season

Water entering each valley consists of: (1) Stream-flow and underflow at upper gaging-station; (2) surface-flow and underflow of washes; (3) artesian flow from wells penetrating lake-bed strata; (4) spring flow from the lake-beds to the inner valley; and (5) rainfall.

Water leaving each valley consists of: (1) Stream-flow and underflow at lower gaging-station; (2) transpiration by cultivated crops and by phreatophytes in the flood-plain; and (3) evaporation from water-surfaces and from wetted land-surfaces.

Surface-flow and underflow--Surface-flow of the river was measured by the Surface-Water Division of the Geological Survey. Surface-flow of the washes in each valley was measured by the Ground-Water Division by three methods, according to the importance of each wash. Temporary gaging-stations, equipped with recorders with an automatic clock-starting device, were placed on 11 large washes in the Duncan-Virden Valley and on nine large washes in the Safford Valley. The recorders used were developed by ground-water engineers during the project and were built in Tucson (Fig. 1). The average total cost of a temporary gaging-station with automatic recorder and wooden gage-well (Fig. 2) was about $40. Staff-gages were placed in about 15 medium-sized washes in each valley. The hydrographs from the recorders and staff-gages were interpreted with current-meter measurements. The flow of small washes in each valley was estimated in the field during the times that they were carrying water.

Underflow of the river at the upper and lower gaging-stations and of washes entering the valleys was estimated from geologic cross-sections, pumping tests, analyses of water from nearby wells and springs, and laboratory tests of the permeability of the underlying materials. The underflow of the river at the upper end of each valley was found to be small and approximately equal to the underflow at the lower end.

Ground-water--The change in ground-water storage, as determined from the net change in water-levels in wells and the specific yield of the water-bearing materials, should balance the equation between the water that enters and the water that leaves each valley. Changes in water-level in the Safford area were computed from monthly measurements in 85 irrigation and domestic wells throughout the valley and semi-monthly or weekly measurements in 79 observation-wells in the river flood-plain. Changes in water-level in the Duncan-Virden Valley were computed from monthly measurements in 39 wells. Maximum-minimum water-level recorders were installed in about 40 wells in the Safford Valley and in five wells in the Duncan-Virden Valley. Weekly-type water-level recorders were installed in six wells in the Safford Valley and in three wells in the Duncan-Virden Valley.

There are two types of ground-water in this region, namely, the artesian water in permeable layers of sand and gravel in the lake-beds and the water in the alluvial fill in the valleys and along the largest washes. Records of about 800 wells were obtained in the Safford Valley and of about 150 wells in the Duncan-Virden Valley, and samples of water were taken from many of these wells. Water-analyses helped to indicate artesian subsurface-springs and return-flow from canals and irrigated fields. Levels have been run to most of the wells and preliminary work has been done for plotting contours of the water-table.

The intake-areas of the artesian aquifers of the lake-beds are probably at the base of the mountains, near the contacts of the hard rocks with the overlying materials. Seepage-runs on washes carrying winter flow show that in the first few miles from the base of the mountains these washes have very heavy losses. Except during heavy floods, the entire winter-flow is absorbed by the channel sand and gravel within a few miles. A part of this water probably penetrates the underlying beds and recharges the artesian supply and a part enters the valleys as wash underflow.

The principal discharge of artesian water occurs from wells and fault-springs. The main areas of artesian water are the valley of Cottonwood Wash and the areas in Safford Valley near Artesia, Geronimo, Pima, and San Jose. The largest artesian well in the area is the Mack Well, near Pima, which flows about 1,350 gallons a minute. The flow from other wells ranges from five to 200 gallons a minute. The largest artesian springs are at Indian Hot Springs, and their total flow is reported as 2,500 gallons a minute.

In the alluvial deposits of silt, sand, and gravel along the Gila River and along some of the major washes, recharge may take place at any point, as the rain penetrates the deposits readily and the streams flowing across them lose heavily where the water-table is below the bed of the stream. There are large deposits of alluvial fill along some of the main tributaries to the Safford Valley, namely, Black Rock, Goodwin, Cottonwood, and Stockton washes. There are few deposits of alluvial fill of any size along the washes leading into Duncan Valley. The irrigation of valley-lands also causes recharge of the ground-water, and seepage-measurements on the canals show that in places they lose heavily.

The discharge of water from the alluvial deposits is from seeps along the Gila River and from irrigation-wells in the river-valleys and in the flood-plains of Black Rock and Goodwin washes. The total quantity of water pumped from irrigation-wells in each valley was determined. The rate of discharge from each well was measured with a weir or current-meter once or twice during the pumping season and the owner of the well kept a record of hours of operation.

Bank-storage--Floods in the river contribute to bank-storage, or temporary storage of water in the alluvial fill near the river itself, as distinguished from channel, or pool storage. Most of this water is returned to the river during a falling stage, except where the water-table had been drawn below the river-level by transpiration of plants or by pumping. Changes in quantity of water in bank-storage along the river were determined to some extent from water-level records on observation-wells, from records of increase or decrease in the flow of the river as shown by seepage-runs, and by four low-flow gaging-stations in the Safford Valley.

Observation-wells were bored or driven along 11 lines across the river-bottoms at intervals of about five miles. Seven to 13 wells were installed about 500 feet apart in each line. In making all of these test-wells, eight-inch augurs were used to the water-table and samples of the water-bearing gravels were taken for hydrologic study. A few of the wells in each line were cased with eight-inch galvanized pipe to a level a few feet below the water-table, and for part of the time water-level recorders were installed on them. The remaining wells in the lines consisted of one-inch pipe with sand-points driven several feet below the water-table with the eight-inch hole above the water-table backfilled around the pipe. Water-levels in the sand-point wells were measured at weekly or semi-monthly intervals. Maximum-minimum strip-recorders were installed in alternate sand-point wells. Staff-gages were installed on the river at each well-line and the river-stage was recorded when the wells were measured.

Table 1--Use of water in tanks at Experiment Station, Safford, May 10 to December 31, 1940

(Figures include evaporation from surface of tank and transpiration from vegetation growing in tank)

Tank No.	Consumptive use, inches									Remarks
	May 10-31	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total	
1	2.2	1.7	6.1	11.6	11.7	11.0	2.4	1.2	47.9	Diameter, 6 feet; water-level, 4 feet; planted with tamarisk; covered with straw, May 31-June 25 (this was done to eliminate evaporation in determination of specific yield); transpiration retarded after first killing frost, October 29
2	2.8	3.7	10.4	14.2	13.2	12.4	3.5	0.9	61.1	Diameter, 6 feet; water-level, 2 feet; planted with tamarisk; covered with straw, May 31-June 22; retarded by killing frost, October 29
3	1.6	4.0	3.3	5.4	5.9	6.4	3.4	1.6	31.6	Diameter, 4 feet; water-level, 4 feet; planted with baccharis; covered with straw, June 1-14; still growing December 31
4	1.7	6.2	10.6	10.0	9.0	9.0	3.6	1.9	52.0	Diameter, 4 feet; water-level, 2 feet; planted with baccharis; covered with straw, June 1-12; still growing December 31
5	3.4	6.4	7.9	7.4	5.9	4.3	2.4	2.0	39.7	Diameter, 2 feet; water-level, 2 feet; same soil as tanks 1 to 4; no vegetation; covered with straw, May 31-June 8
6	2.2	5.6	6.3	6.0	5.3	4.4	2.8	1.4	34.0	Diameter, 2 feet; water-level, 2 feet; river-bed materials; no vegetation; covered with straw, May 31-June 8
7	2.0	3.8	3.1	3.6	2.9	1.8	1.4	1.2	19.8	Diameter, 2 feet; water-level, 2 feet; alkali-encrusted silt; no vegetation; covered with straw, May 31-June 8
-	6.3	11.2	10.2	9.2	6.3	5.1	2.8	2.0	53.1	Water-evaporation in Safford Valley; average from all pans (for comparative purposes)

Seepage-runs were made on the river in both valleys at intervals of about one month during the summer but none were made in the winter because large flows prevented accurate measurements. In the seepage runs the river-flow was measured at intervals of three to five miles throughout its length between the control gaging-stations, and all inflow and diverted surface-water was measured between successive sections. Water-samples were taken at every river-measurement and analyzed for mineral content. The seepage-measurements and water-analyses indicated regions of gain or loss in flow of the river, the approximate amount of such gain or loss and its source. Gains were caused by subsurface return-flow from canals and irrigated fields and by underflow from washes; losses were caused by withdrawals from ground-water storage by irrigation-wells, by evaporation from free water-surfaces and from wetted land-surface and by transpiration of river-bottom vegetation.

The four low-flow gaging-stations in the Safford Valley were installed on the river at approximately equal intervals between the upper and lower gaging-stations. They are equipped with weekly recorders and are used to measure small changes occurring during low flow, and in effect, to obtain a continuous seepage-record. They have proved valuable not only in recording changes in flow from day to day, but also show diurnal changes in flow resulting from the water-requirements of the river-bottom phreatophytes.

Transpiration--The water-requirements of cultivated crops are being checked by botanical methods. There are no data on the use of water by cottonwood, tamarisk, and baccharis, and such data are being obtained by four methods, as follows:

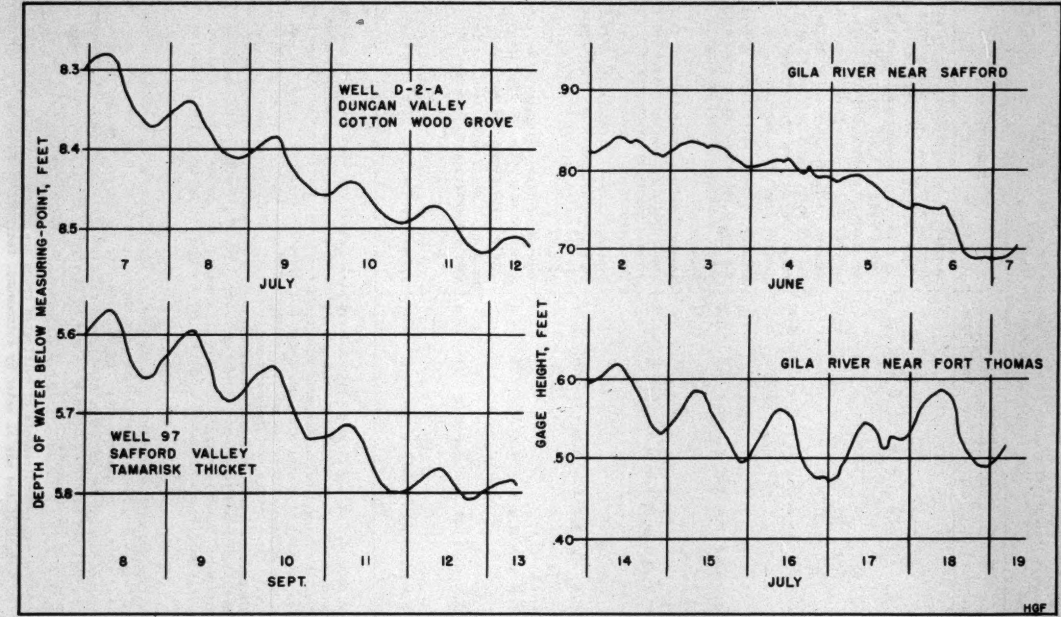


Fig. 4--Hydrographs of shallow wells and of Gila River showing fluctuations caused by transpiration and evaporation

An experiment station was established in the river-bottom near Safford in April, 1940, and seven soil-tanks (Fig. 3) were installed May 10, 1940. Two of the tanks contain salt-cedar or tamarisk, two contain bata-mote or baccharis, and the other three contain bare soil. The water-level is measured in each tank every morning and water is added, when necessary, to keep it at a nearly constant depth (Table 1).

Water-stage recorders were maintained on a well in a tamarisk-thicket at the Experiment Station and on wells at other points in the river-bottoms in each valley. These recorders, in addition to measuring bank-storage from floods, show diurnal fluctuations of the water-table in response to water-requirements of the vegetation (Fig. 4). Water-consumption can be computed from these daily fluctuations by the method developed by White [4].

The four low-flow gaging-stations on the river show diurnal changes in flow of as much as five second-feet in a total flow of 35 second-feet (Fig. 4). Daily peak-flow and low-flow in the river occurred at almost the same time as the peak- and trough-stages of the water-table as shown by recorders in wells nearby.

Transpiration was measured by the botanical methods described by Rabe [5]. Measurements of water required by plants were made by this method one day each month during the growing season. Cuttings of alfalfa, tule, cottonwood, willow, tamarisk, and baccharis were made at hourly intervals from sunrise to sunset. Each sample was weighed immediately after being cut and then placed in the Sun for an hour. It was then reweighed and laid aside for artificial drying. The loss of weight during the first hour affords an index of the rate of transpiration. Hourly measurements were kept of relative humidity, evaporation, and temperature during the day that cuttings were transpiring. After a test was completed the cuttings were air-dried for several days, oven-dried, and then burned to ash. They were weighed individually at each of these stages of the drying process. To correlate these results with field-conditions, it was necessary to clear a representative area of each type of vegetation and weigh it, dry representative portions and burn them to ash to estimate the water used by growing plans.

Rainfall and evaporation--The Experiment Station near Safford also includes a weather-station, with Class-A evaporation-pan, anemometer, rain-gage, maximum and minimum thermometers, and a psychrometer. Daily observations of meteorological conditions are recorded. During the summer of 1940 a standard weather-station was operated daily in the Duncan-Virden Valley, but in the winter it was visited once a week.

Rainfall is measured at the weather-stations and at 12 other rain-gages in the two valleys. There are also several rain-gages on the outlying gravel-covered mesas.

Evaporation from free water-surfaces is measured at daily or weekly intervals with five evaporation-pans in the Safford Valley and four in the Duncan-Virden Valley. Evaporation from wetted soil is measured with three of the seven tanks at the Experiment Station (Table 1). Evaporation from fields is computed from estimates of the areas wetted by irrigation.

Results--The data gathered during 1940 were summarized at the end of the year. The water-equation for the Duncan-Virden Valley in the calendar year 1940 shows an error of 637 acre-feet. The rainfall on non-irrigated desert-areas within each valley was assumed to be equal to the evaporation and transpiration from these areas.

Preliminary water-equation, Duncan-Virden Valley, 1940

Water entering valley	Acre-feet
Gila River at Fuller's Ranch gaging-station	146,300
Precipitation	
Water-surface of river	350
Water-surface of canals	20
Irrigated lands	9,350
Wetted sand in river-bottom	890
Transpiration area in river-bottom	2,350
Artesian water entering the valley through springs	1,000
Underflow of large washes	2,000
Surface-flow of washes	7,500
Total	169,760

Preliminary water-equation, Duncan-Virden Valley, 1940--Concluded

Water leaving valley	Acre-feet
Gila River at Clifton gaging-station	130,670
Evaporation from water-surfaces	
Water-surface of river	1,535
Water-surface of canals	86
Water-surface of irrigated land	675
Evaporation from wetted land-surfaces	
Wetted sand in river-bottom	1,918
Transpiration and evaporation	
River-bottom vegetation	10,130
Irrigated area	24,183
Total	169,197
Water entering valley less water leaving valley	563
Gain in ground-water storage	1,200
Error of balance	637

References

[1] Surface water supply of the United States, 1938, Part 9, Colorado River Basin, U. S. Geol. Surv. W.-S. Paper 849, pp. 234-239, 1939.

[2] A. T. Schwennesen, Geology and water resources of the Gila and San Carlos Valleys in the San Carlos Indian Reservation of Arizona, U. S. Geol. Surv. W.-S. Paper 450-a, 1919.

[3] M. M. Knechtel, Geology and ground-water resources of the valley of the Gila River and San Simon Creek, Arizona, U. S. Geol. Surv. W.-S. Paper 796-f, 1938.

[4] W. N. White, A method of estimating ground-water supplies based on discharge by plants and evaporation from soil, U. S. Geol. Surv. W.-S. Paper 659-a, p. 82, 1932.

[5] Oran Rabe, Water utilization by trees, with special reference to the economic forest species of the North Temperate Zone, U. S. Dept. Agric. Misc. Publ. 257, p. 20, 1937.

U. S. Geological Survey,
Tucson, Arizona

COEFFICIENTS OF STORAGE AND TRANSMISSIBILITY OBTAINED FROM PUMPING TESTS IN THE HOUSTON DISTRICT, TEXAS

C. E. Jacob

(Published with the approval of the Director, U. S. Geological Survey)

An investigation of the ground-water supply of the Houston District, in Texas, has been in progress since December, 1930, under the general direction of O. E. Meinzer, Geologist-in-Charge of the Division of Ground Water of the Geological Survey. The Houston District, as the term is used here, comprises all of Harris County and parts of Montgomery, Waller, and Fort Bend counties, lying between the Trinity and Brazos rivers. The investigation in this area has consisted primarily of inventorying well-logs and pumpage-records, of obtaining water-level data and information regarding the chemical character of the ground-water, and wherever possible of correlating these data.

The present more intensive phase of the investigation was begun in the fall of 1938 and is being conducted by the Survey in cooperation with the Texas State Board of Water Engineers and the City of Houston. W. N. White is in direct charge of the work. As part of the investigation, 13 deep test-wells were drilled by the City of Houston during the summer of 1939. Information regarding the results of this test-drilling are given in a recent report [see 1 of "References" at end of paper]. A study is now being made of the geology of the area, correlations being based chiefly on electrical logs of oil-tests and water-wells. A progress report [2] concerning the present status of the investigation summarizes conditions with respect to the present and probable future effect of pumpage on the artesian head, the decline of water-levels in the outcrop-area, the depletion of storage, and the possibility of salt-water intrusion.

In the fall of 1939 the writer, chiefly with the assistance of W. F. Guyton, of the Geological Survey, conducted a total of 21 pumping tests on Houston city-owned wells to determine coefficients of storage and transmissibility. Tests were run on 16 supply-wells, at four of the city's seven well-fields (see Fig. 1), and on five of the then recently completed test-wells. A brief description of these tests and a summary of the results are included in the progress-

Table 1--Summary of results of recovery-tests of City of Houston municipal supply- and test-wells, September and October, 1939

Plant (1)	Well (2)	Date of test, 1939 (3)	Alignment of data (4)	Discharge Q, gpm (5)	Transmissibility T, gpd/ft (6)	Total thickness sand m, feet (7)	Approximate range depths, feet (8)		Effective average value K = T/m, gpd/ft^2 (9)
							From	To	
Central	C-16	Oct. 27	Good	1,260	60,000	269	1144	1517	220
	F- 1	Oct. 3	Fair	1,370	117,000	344	888	1488	340
	F- 5	Oct. 10	Fair	1,250	87,000	318	885	1443	270
	F-10	Oct. 17	Poor	1,050	117,000	359	880	1497	330
	F-11	Oct. 24	Good	1,300	54,000	253	498	944	210
	F-12	Oct. 19	Good	1,600	52,000	294	1180	2020	180
Heights	5	Oct. 25	Good	2,050	82,000	245[a]	408	1860	330
	6	Oct. 11	Good	1,700	95,000	324[a]	581	1225	290
	7	Sep. 28	Fair	1,500	105,000	591[a]	561	1454	180
	8	Oct. 18	Good	1,840	116,000	400[a]	556	1240	290
North East	1	Oct. 13	Good	1,880	57,000	237[a]	1013	1872	240
	2	Sep. 30	Fair	2,030	95,000	404[a]	461	1279	240
Scott Street	2	Oct. 12	Poor	1,540	120,000	157	1326	1502	760
	3	Oct. 5	Good	2,100	72,000	222	553	919	320
	4	Oct. 18,19	Good	2,800	111,000	278	1037	1758	400
	5	Sep. 20,21	Fair	1,770	55,000	285	470	949	190
Test-wells									
At Alief	4-A	Oct. 10	Poor	29	35,000	70	---	---	500
	5	Oct. 10	Nil	43	------	--	---	---	---
At South Houston	8	Oct. 11	Poor	38	9,800	30	---	---	325
	9	Oct. 11	Nil	39	------	--	---	---	---
At Westfield	10-A	Sep. 26	Good	50	9,600	64	---	---	150

[a] Based on screen-settings; all others based on drillers' logs or on electrical logs.

report [2] referred to above. They are given in greater detail here. Further interpretation as to the significance of the results and their application to general problems in the Houston District is given in a paper by Guyton published elsewhere in these Transactions [pp. 756-772].

In running pumping tests on the supply-wells it was necessary to modify the usual technique somewhat. (As used here, "pumping test" does not mean a test of the kind made by the driller to check the performance of the well and pump-installation and to determine the specific capacity, but rather a test primarily for determining the hydrologic properties of the water-producing beds.) In the ideal set-up for tests of this kind one has a pumping well and a number of observation-wells all penetrating the full thickness of a given aquifer, and by observing the decline and subsequent recovery of head in the several wells during and following a closely controlled period of pumping, with all extraneous factors eliminated, one is able to obtain the desired information. However, the set-up at most of the plants at which tests were run was far from ideal from this standpoint. At a given plant, for example, Scott Street Plant (see Fig. 2), there might be several wells tapping from as few as two or three sands to as many as nine sands, there being a comparable or even greater variation in the number and length of screens in the different wells. Moreover, the tests had to be run at a time when the consumption of water was comparatively high and because of the lack of storage-facilities and the inadequacy of interconnecting mains it was not practicable to shut down a given plant completely for any length of time. Therefore, it was necessary to adapt the test-procedure to the normal routine of operation of the plants. This was done by working with one well a week at each plant. The designated well was allowed to remain idle for at least five days, during which time the intermittent operation of the other wells at the same plant went on as usual. After this period of rest the well was pumped for a period of about 24 hours, usually beginning early in the morning. Following the shut-down, periodic measurements were made of the recovery of the water-level in the pumped well, from which values of transmissibility [3] were determined. The results of the "recovery-tests" are summarized in Table 1.

Measurements of depth to water-level in the supply-wells were made between the casings and the discharge-lines by means of a 200-foot steel tape. With one man measuring and another recording, readings could if necessary be made as often as every two minutes, with depths to

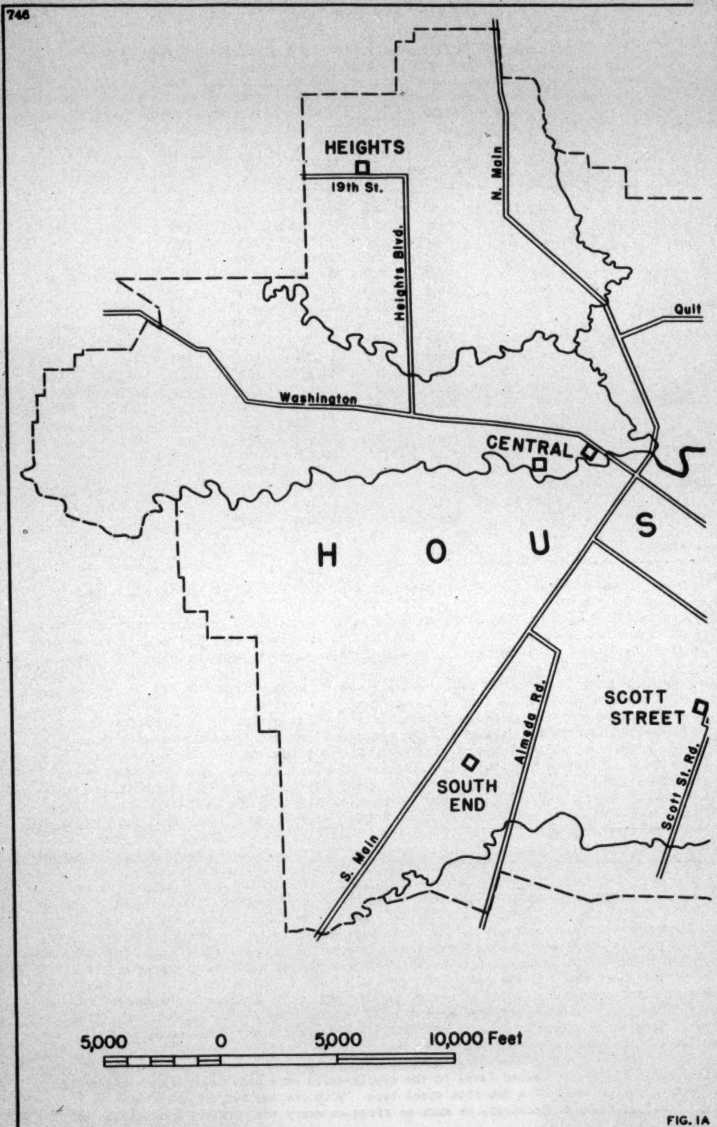

746
HEIGHTS
19th St.
Heights Blvd.
N. Main
Quit
Washington
CENTRAL
H O U S
Almeda Rd.
SCOTT STREET
SOUTH END
Scott St. Rd.
S. Main
5,000
0
5,000
10,000 Feet

FIG. 1A

Fig. 1--Map of Houston, Texas, showing location of city pumping plants

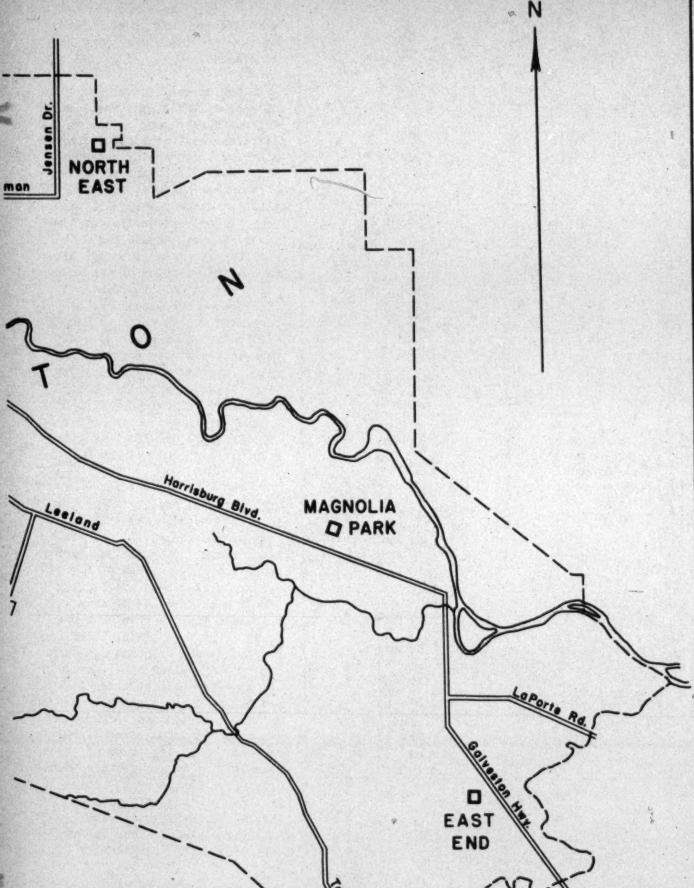

N
NORTH EAST
Jensen Dr.
man
T O N
MAGNOLIA PARK
Harrisburg Blvd.
Leeland
LaPorte Rd.
Galveston Hwy.
EAST END
Telephone Rd.

FIG. 1B

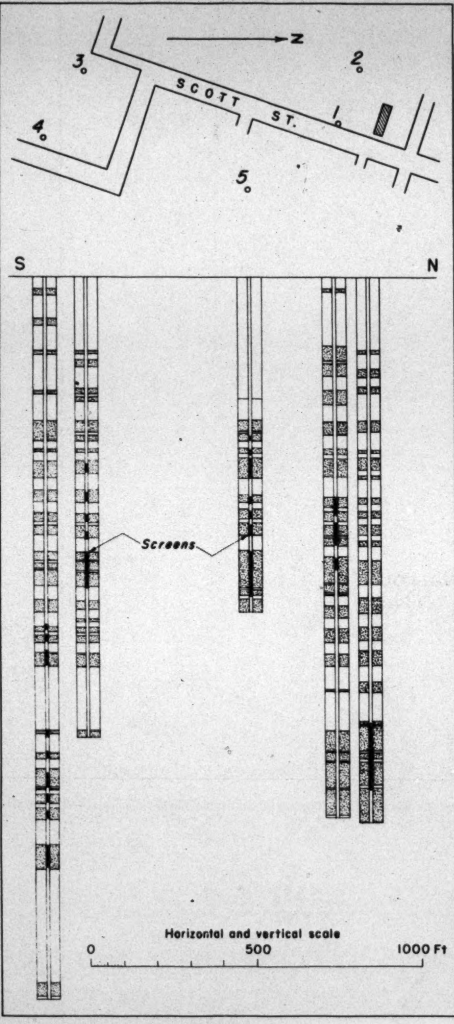


Fig. 2--Location of wells at Scott Street Plant, Houston, Texas, and columnar sections based on well-logs

water ranging well over 100 feet. However, the tests were for the most part run with only one man on the job, working in shifts during the more prolonged tests. In a few cases wells were inaccessible to measurement by tape and measurements by air-line were used.

During the recovery period of many of the supply-wells measurements were made of the interference-effects produced by starting and stopping pumps on other wells which are screened in the same sands at the same plants. Where possible it was prearranged that sufficient time should elapse between the stopping of the well being tested and the starting of the well which was to take its place so that the recovery could be established sufficiently to permit extrapolation over the succeeding periods of the test, during which interference was observed. From these "interference-tests" there were determined values of transmissibility and coefficients of storage [4, p. 894], as given in Table 2.

The word "interference" is used here advisedly. According to Slichter [5], "The interference of two wells, in the technical sense, is determined by a comparison of the flow of one of two wells when both are flowing freely with the flow of each well when the other is shut off." It is a function of the total available head (assumed constant for flowing wells), the extent of the water-bearing beds, and the diameter and spacing of the wells. Interference is often expressed in terms of relative decrease in yield. However, when applied to wells other than flowing wells the term "interference" as thus defined may lose its significance, quantitatively speaking, because the effect described then is dependent not only on the factors enumerated above but also on the characteristics of the pumps and of the prime movers. In the general case of non-flowing wells, the relative decrease in head resulting from interference may be more significant than the relative decrease in discharge.

Table 2--Summary of results of interference-tests of City of Houston municipal supply-wells, September and October, 1939

Plant (1)	Well (2)	Date of test, 1939 (3)	Limb of curve (4)	Alignment of data (5)	Interference[a] produced by well (6)	Value (r^2/t) for $u = 0.1$, ft^2/sec (7)	Value of s for $-Ei(-u) = 1.823$, feet (8)	Corrected[b] value s, feet (9)	Change discharge ΔQ, gpm (10)	Coefficient storage S (11)	Transmissibility T, gpd/ft (12)	Total[c] thickness sand m, feet (13)	Approximate range depths, feet (14)		Effective average value $K = T/m$, gpd/ft^2 (15)
													From	To	
Central	F-1	Oct. 3	V	Fair	F- 5 (r)	200	2.17	2.17	-1,260	3.8×10^{-4}	121,000	318	885	1443	380
			VI	Fair	F-10 (r)	115	2.06	2.06	-1,330	7.2×10^{-4}	134,000	359	880	1497	370
	F-5	Oct. 10	II	Good	F-10 (d)	140	1.86	1.86	+1,020	5.1×10^{-4}	114,000	359	880	1497	320
			III	Good	F- 1 (d)	170	2.51	2.51	+1,250	3.8×10^{-4}	104,000	344	888	1488	300
			IV	Poor	F-12 (d)	85	2.40	2.74	+1,600	8.9×10^{-4}	122,000	294	1180	2020	410
			V	Fair	F-10 (r)	145	1.64	1.64	-1,020	5.5×10^{-4}	130,000	359	880	1497	360
			VI	Good	F- 1 (r)	157	2.16	2.16	-1,250	4.8×10^{-4}	121,000	344	888	1488	350
Heights	7	Sep. 28	II	Good	8 (r)	88	2.37	2.86	-1,840	9.4×10^{-4}	134,000	400	556	1240	340
North East	1	Oct. 13	II	Poor	2 (d)	90	0.51	1.36	+2,030	21.5×10^{-4}	313,000	404	461	1279	770
Scott Street	2	Oct. 12	II	Good	4 (r)	165	4.00	4.00	-2,800	5.5×10^{-4}	147,000	278	1037	1758	530
	3	Oct. 5,6	II	Good	1 (d)	69	1.73	2.67	+ 250	1.8×10^{-4}	20,000	191	651	905	100
			III	Fair	1 (r)	69	1.55	2.39	- 250	2.0×10^{-4}	22,000	191	651	905	110
			IV	Good	5 (r)	52.4	5.52	5.52	-1,770	7.9×10^{-4}	67,000	285	470	949	230
	4	Oct. 19	II	Fair	2 (d)	172	2.06	6.98	+1,540	1.7×10^{-4}	46,000	157	1326	1502	290
	5	Sep. 20,21	V	Poor	1 (r)	11.8[e]	1.80[f]	2.49[f]	- 250	2.5×10^{-4}	47,000	191	651	905	250
			VII	Fair	3 (r)	53.6	4.20	4.69	-2,100	10.8×10^{-4}	94,000	222	553	919	420

[a] d = drawdown; r = recovery. [b] Corrections for Heights Well 7 and for North East Well 1 based on screen-settings; all others based on drillers' logs or on electrical logs. [c] Thicknesses given for Heights Well 7 and for North East Well 1 based on screen-settings; all others based on drillers' logs or on electrical logs. [e] For $u = 0.01$. [f] For $-Ei(-u) = 4.038$.

Table 3--Pertinent data regarding test of Scott Street Well 3

Period test (i)	Time of occurrence changes in discharge, t_i	Change discharge ΔQ_i, gpm	Well in which change occurred	Distance from Well 3 to well in question r_i, feet
	h m 1939			
0	08 02, Oct. 4	+2,100	3	a
1	08 03, Oct. 5	-2,100	3	a
2	09 58, Oct. 5	+ 250	1	790
3	15 03, Oct. 5	- 250	1	790
4	02 48, Oct. 6	-1,770	5	605

[a] "Effective" radius of Well 3 not determined.

this because of the discharge-head relations of the particular motor-pump combinations used. The pumping test described above is spoken of as an "interference-test" because in a sense it entails measurements of the relative decrease in head, from which if need be the theoretical relative decrease in discharge could be determined. In fact, it would seem that it is only in this way that accurate measurements of interference are to be made if the intent of the original definition is to be adhered to. Assuming a complete knowledge of the motor- and pump-characteristics, it would be possible a priori to determine also the approximate actual relative decrease in discharge. (This applies in general to the mutual interference of two wells only.)

It has been shown elsewhere [3, 6] that the drawdown produced by a completely penetrating well discharging water at a constant rate from an infinite aquifer of uniform transmissibility is

$$s = c[-Ei(-u)]$$

where $c = Q/4\pi T$, Q being the discharge of the well, and T the transmissibility (discharge per unit-width per unit hydraulic gradient); and where $u = r^2/a^2 = r^2S/4Tt = b/t$, r being the distance from the discharging well, t the time elapsed since the discharge began, and S the coefficient of storage (assumed constant).

The function Ei(u), known as the "exponential integral," is computed by means of the convergent series

$$0.5772 + (1/2)\log_e u^2 + u + u^2/2\cdot 2! + u^3/3\cdot 3! + \ldots\ldots$$

Thus, $s/c = -Ei(-u) = -0.5772 - (1/2)\log_e u^2 + u - u^2/2\cdot 2. + \ldots\ldots$

In a previous paper by the writer [6], referred to above, the initial piezometric surface was arbitrarily chosen as the plane of reference, $h = 0$. The drawdown was expressed simply as $(-h)$, the head, h, being taken positive upward. Here the drawdown, $s = (h_0 - h)$, is taken positive downward, h_0 being the initial value of the head.

An additional change of notation has seemed desirable. In the paper previously referred to, c was taken as negative for a discharging well, which was considered analogous to a "sink". It now seems desirable to have Q (and therefore c also) positive for a discharging well. In the last analysis this procedure is correct, for Q may be considered to be the scalar product of two parallel vectors, $\overline{V}$ and $\overline{A}$, the latter being represented in magnitude by the area of the cylindrical surface bounding the aquifer at the well-face and in direction by the outward directed normal of that surface. (The "outward"-directed normal is actually directed inward, that is, toward the well, though it is directed outward with respect to the aquifer. In other words, the well-face is considered to be part of the "closed surface" bounding the aquifer.)

If the drawdown, s, can be measured for one or more values of r and for several values of t, the constant discharge, Q, being known, values of T and S may be determined by means of a graphical method devised by Theis [6, p. 582]. This graphical method may be extended to apply to successive drawdowns (and recoveries). Assuming that the decline of the piezometric surface does not involve diminution of the transmissibility through unwatering of the topmost part of the aquifer, the drawdowns and recoveries in a given well produced by (instantaneous) finite changes in the discharge of different wells (occurring either simultaneously or at different times) are algebraically additive, recoveries being considered negative drawdowns. For example, if a finite change in the discharge of a particular well occurs at time t_1, the head at time t thereafter is given by $h' = (h - s') = (h_0 - s - s')$. Similarly, following a second finite change in discharge occurring at time t_2, $h'' = (h' - s'') = (h_0 - s - s' - s'')$, and so on. Thus, in general

$$h^{(n)} = h_0 - \sum_{i=0}^{n} s^{(i)}$$

Parentheses are employed here to indicate primes of the order given by the enclosed letters. The general drawdown-term is defined by

$$s^{(i)} = h^{(i-1)} - h^{(i)} = (\Delta Q_i/4\pi T)\left\{-Ei[-r_i^2 S/4Tt^{(i)}]\right\}$$

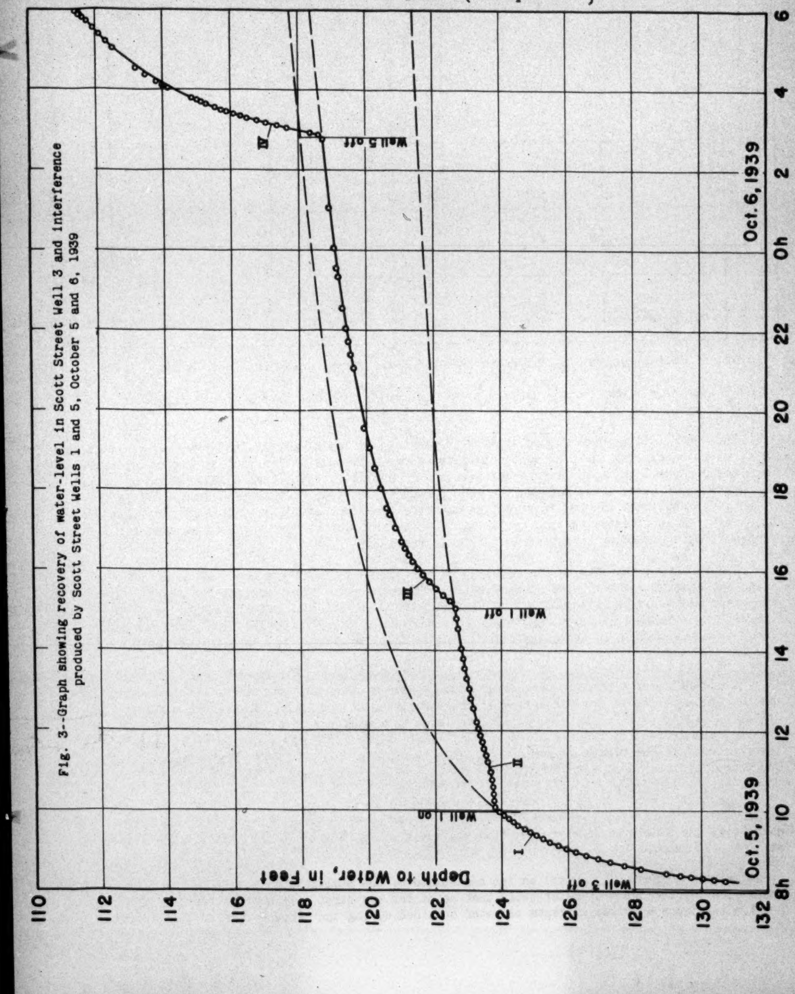


Fig. 3--Graph showing recovery of water-level in Scott Street Well 3 and interference produced by Scott Street Wells 1 and 5, October 5 and 6, 1939

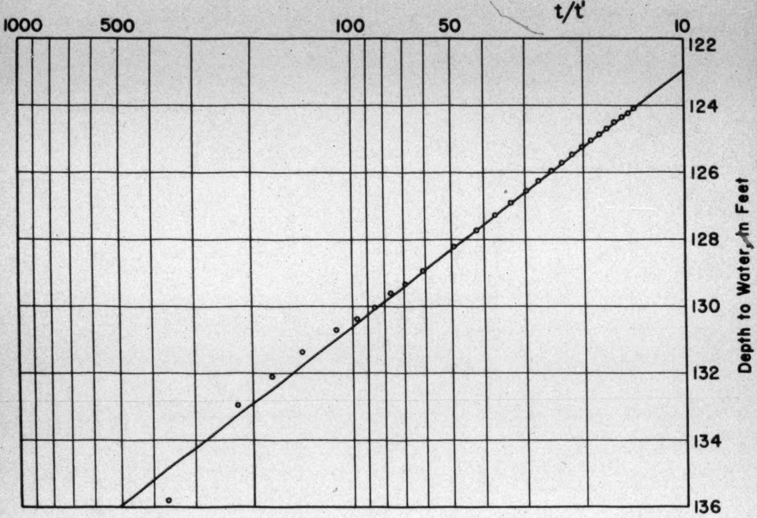


Fig. 4--Semi-logarithmic graph of recovery of Scott Street Well 3, October 5 and 6, 1939

where r_i is the distance to the particular well in which a finite change in discharge, ΔQ_i, occurred at time $t_i = [t - t^{(i)}]$.

The "graphical method" may be applied to the i-th period of a test, between time t_i and time t_{i+1}, by extrapolating the previous limb of the curve, given by $h^{(i-1)}$, and by taking the drawdown (or recovery) as the difference between $h^{(i-1)}$ and $h^{(i)}$, the latter being defined by actual measurements of water-level made during that period of the test. (This procedure is valid provided in general that changes in discharge do not occur simultaneously in different wells.) Perhaps this may be illustrated best by taking the test of Scott Street Well 3 as an example. Pertinent data regarding this test are given in Table 3.

Figure 2 is a map showing the location of the supply-wells at the Scott Street Plant and a north-south section showing the screen-settings for each well. The sections for wells 1 to 4 are based on the drillers' descriptions of rotary samples. Material described as "sand" or "gravel" is indicated by stippling; material described as "clay", "shale", or "gumbo" is indicated by a blank space in the graphic log. The section for Well 5 is based on the electrical log for that Well.

Measurements of depth to water-level made in Well 3 after the shut-down are plotted in Figure 3. The equation of the first limb of the curve, designated I, may be seen from the foregoing equations to be $h' = (h_0 - s - s')$. For large values of t with a small (constant) value of r ($= r_w$, the "effective" radius of the pumped well), $(s/c) \approx [-0.577 - 2.30 \times \log_{10}(r_w^2 S/4Tt)]$, the remainder of the series becoming small. Similarly, $(s'/c') \approx [-0.577 - 2.30 \times \log_{10}(r_w^2 S/4Tt')]$. Therefore, since $c = -c' = Q/4\pi T$,

$$(h_0 - h') = (s + s') \approx 2.30(Q/4\pi T)\log_{10}(t/t')$$

where t is the time elapsed since the well started pumping, and t' is the time elapsed since the well stopped pumping [3, p. 522].

Taking the "measuring point" on the base-plate of the pump-head as the datum for measurements of head, the depth to water below that point for the first period of the test is given by $(-h')$. In Figure 4 values of depth to water obtained during the recovery-period are plotted against values of (t/t') on a logarithmic scale. These points fall fairly well on a straight line, as would be required by the foregoing equation. Assuming that h_0 remains constant throughout the test

$$(h_0 - h'_1) = 2.30(Q/4\pi T)\log_{10}(t/t')_1$$

and

$$(h_0 - h'_2) = 2.30(Q/4\pi T)\log_{10}(t/t')_2$$

where $(-h'_1)$ and $(-h'_2)$ are values of depth to water for $(t/t') = (t/t')_1$ and $(t/t') = (t/t')_2$, respectively. Subtracting one equation from the other and solving for T, choosing

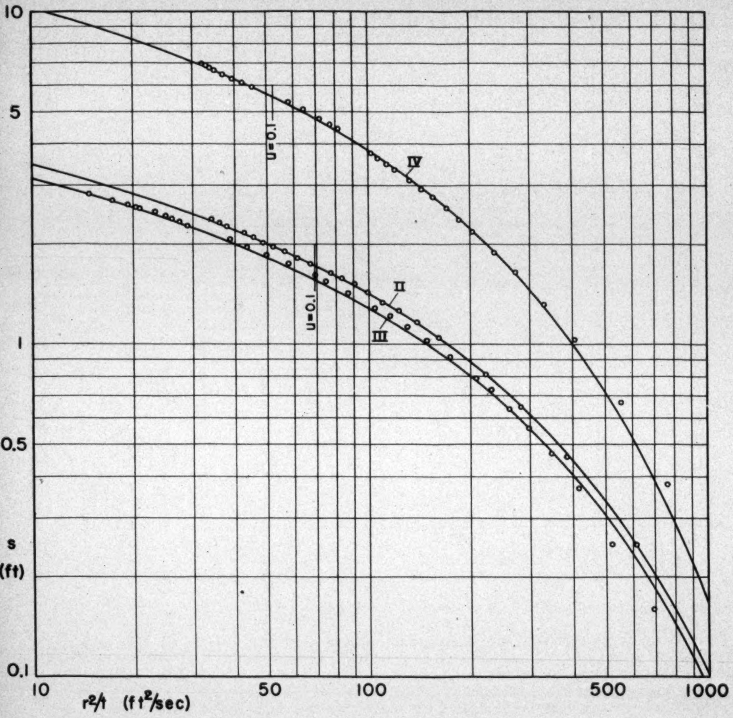


Fig. 5--Logarithmic graph of interference-effects observed in Scott Street Well 3 during recovery-period, October 5 and 6, 1939

$(t/t')_2 = 10(t/t')_1$

$$T = 2.30[Q/4\pi(h'_1 - h'_2)]$$

A value of transmissibility was thus determined for Scott Street Well 3 from the straight line drawn through the points plotted in Figure 4. The value of Q for this well was 2,100 gallons per minute [see column (5), Table 1] or about 3,000,000 gallons per day. Taking $(t/t')_1 = 10$ and $(t/t')_2 = 100$, $T = 2.30\ [3{,}000{,}000/4\pi(-122.9 + 130.6)] = 72{,}000$ gpd/ft, as given in column (6) of Table 1.

The "static" level would theoretically be attained when $(t/t') = 1$. The depth to water-

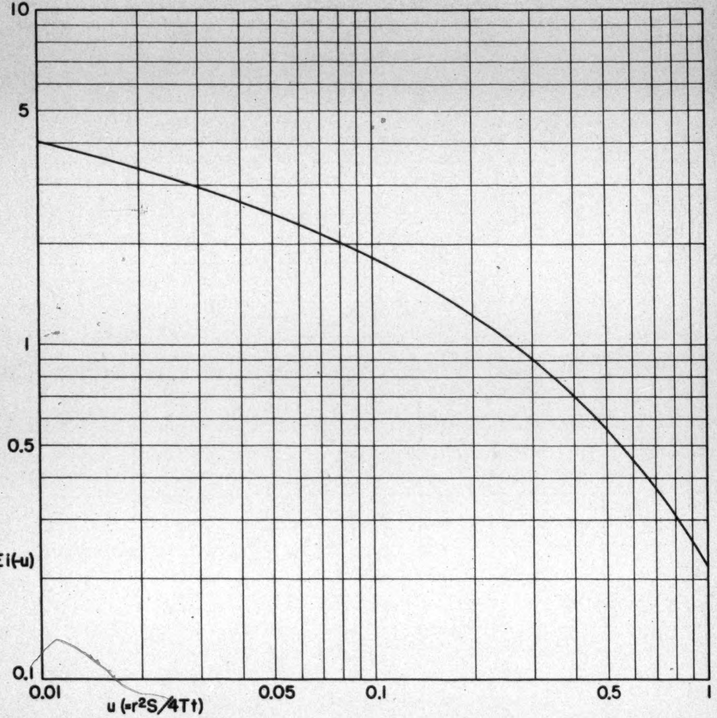


Fig. 6--Logarithmic graph of the exponential-integral "type curve"

level would then be $-h_0 = -h'_1 + (h'_2 - h'_1) = (2 \times 122.9) - 130.6 = 115.2$ feet.

According to the driller's log, the aggregate thickness of the sands in which screens are set in Well 3 is 222 feet. These sands range in depth from about 553 feet to 919 feet. Dividing the transmissibility, T, by the thickness, m, we obtain $K = T/m = 72{,}000/222 = 320$ gpd/ft^2 [7], as given in column (9). In order to determine from this the value of Meinzer's coefficient of permeability it is necessary to apply a correction for the variation of viscosity with temperature. (Corrections for the variation of viscosity with pressure, for the variation of density with temperature and with pressure, and for the variation of gravity may be neglected here.) The temperature of the water discharged by Well 3 is reported as being 79° F (about 26° C). The viscosity of water at this temperature is about 0.87 centipoise; and at standard temperature (60° F or 15°55 C) it is 1.123 centipoises. Thus the numerical value of the effective average coefficient of permeability is $320 \times 0.87/1.12 = 250$.

By changing the abscissas the straight line in Figure 4 was transformed into curve I in Figure 3, extending over the succeeding periods of the test as a broken line. By taking differences between the ordinates of points plotted for the second period of the test and the corresponding ordinates for the extrapolated portion of limb I, there were determined values of drawdown, $s'' = (h' - h'')$. These data were plotted on logarithmic coordinates in Figure 5 against the corresponding values of (r_2^2/t''), giving the curve marked II. Here r_2 is the distance from Well 3 to

Table 4--Summary of values of K and S determined from recovery- and interference-tests, Houston, Texas

Plant	Altitude land-surface, feet (approx.)	Approximate range depth sands, feet		Average value[a] K, gpd/ft^2		Average coefficient storage S
		From	To	From recovery-tests	From interference-tests	
Central	50	498	944	210 (1)		
		880	1500±	310 (2)	350 (6)	5.0×10^{-4}
		1144	1517	220 (1)		
		1180	2020	180 (1)		
Heights	72	408	1860	330 (1)		
		560	1450±	250 (3)	340 (1)	9.4×10^{-4}
North-east	55	461	1279	240 (1)		
		1013	1872	240 (1)		
Scott Street	50	470	950±	260 (2)	220 (4)	5.6×10^{-4}
		1040	1760±	400 (1)	410 (1)	3.6×10^{-4}
Averages........................				270	320	5.4×10^{-4}

[a] Figures in parentheses give number of determinations upon which average is based.

Well 1, about 790 feet. t" is the time, in seconds, elapsed from the time Well 1 started pumping

The parameters S and T were next determined by the "graphical method," which consists of fitting the points plotted in Figure 5 to the "type-curve" in Figure 6. The abscissa and ordinate of the arbitrarily chosen point on the type-curve are respectively $u = 0.1$ and $-Ei(-u) = 1.823$. The abscissa and ordinate of the corresponding point on curve II in Figure 5 are, respectively, $(r^2/t) = 69$ ft^2/sec and $s = 1.73$ feet [see columns (7) and (8) of Table 2]. In order to compensate for the partial overlapping of the screens in wells 1 and 3 there was applied to this value of s an approximate correction. This correction allows for the effect of flow from sands tapped by the "observation"-well but not tapped by the well producing the interference, through the screens and casing of the observation-well, into sands common to both wells. The effect of such flow is to reduce the drawdown in the observation-well. Accordingly values of observed drawdown given in column (8) of Table 2 were increased to what they theoretically would have been assuming all sands tapped by a given well to have the same transmission-constant and the same "static" head.

The aggregate thickness of sands in which the screens in Well 3 at the Scott Street Plant are set is 233 feet (see Fig. 2). The thickness of sands common to both Well 3 and Well 1 is 151 feet. If the foregoing assumptions were valid, the drawdown observed in Well 3 when Well 1 is pumping would be continuously (151/233) times too small. Therefore, if the observed drawdown is 1.73 feet [column (8), Table 2], the actual drawdown should be about 1.73(233/151) = 2.67 feet [column (9)]. Obviously neither of the assumptions is strictly valid, and the correction must therefore be regarded merely as an approximation "in the right direction."

From the known value of change in discharge, $\Delta Q = +250$ gpm or +360,000 gpd, the value of T was first determined

$$T = \Delta Q[-Ei(-u)]/4\pi s = 360{,}000 \times 1.823/(4\pi \times 2.67) = 20{,}000 \text{ gpd/ft}$$

as given in column (12). The aggregate thickness of sand based on the log of Well 1 being 191 feet, the value of average K is in this case about 100 gpd/ft^2.

Taking the value of T thus obtained, the value of the storage-coefficient, S, was determined from

$$S = 4Tu/(r^2/t) = [4(20{,}000/86{,}400 \cdot 7.48)0.1]/69 = 1.8 \times 10^{-4}$$

By a similar procedure, curves III and IV in Figure 5 were obtained. These curves were analyzed by the graphical method, giving additional values of S and T found in columns (11) and (12) of Table 2.

The information given in Tables 1 and 2 under the heading "alignment of data" indicates approximately the degree to which the plotted data conform to theory. Values of K and S determined from tests for which the alignment of data was "fair" or "good" are summarized in Table 4.

References

[1] N. A. Rose, W. N. White, and Penn Livingston, Exploratory well drilling in the Houston district (in preparation).

[2] W. N. White, N. A. Rose, and W. F. Guyton, Progress report on the ground-water resources of the Houston district, Texas State Board Water Eng., Austin, 44 pp., mimeo., November, 1940.

[3] Charles V. Theis, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage, Trans. Amer. Geophys. Union, pp. 519-524, 1935.

[4] Charles V. Theis, The significance and nature of the cone of depression in ground-water bodies, Econ. Geol., v. 33, pp. 889-902, 1938.

[5] Charles S. Slichter, The motions of underground waters, U. S. Geol. Surv. W.-S. Paper 67, p. 95, 1902.

[6] C. E. Jacob, On the flow of water in an elastic artesian aquifer, Trans. Amer. Geophys. Union, pp. 574-586, 1940.

[7] This K is the same as Slichter's k, which he termed the "transmission-constant" and which he defined as "the quantity [volume] of water that would be transmitted in unit-time through a cylinder of the soil of unit-length and unit cross-section under unit-difference in head at the ends." See U. S. Geol. Surv. 19th Ann. Report, p. 323, 1899; also, U. S. Geol. Surv. W.-S. Paper 140, p. 11, 1905.

[Note: For discussion of above paper by M. King Hubbert, see p. 770.]

U. S. Geological Survey,
Jamaica, New York

APPLICATION OF COEFFICIENTS OF TRANSMISSIBILITY AND STORAGE TO REGIONAL PROBLEMS IN THE HOUSTON DISTRICT, TEXAS

W. F. Guyton

Introduction--The Houston District, as the term is used in this paper, comprises an area between the Trinity and Brazos rivers in Harris County and parts of Montgomery, Waller, and Fort Bend counties, Texas. It consists of a plain of low relief that lies not far above sea-level, and is a part of the West Gulf Coastal Plain. A part of the District is shown in Figure 1.

Large quantities of ground-water are pumped in the Houston District from a succession of beds of sand that occur between 300 and 1,900 feet below the surface. These sands are interbedded with relatively impermeable clays. The formations range in age from Miocene to Recent and were deposited during several cycles of marine and continental deposition. They may be classified into several zones which are predominantly clay or predominantly sand, but in which the individual beds at most horizons can not be traced very far. Most of the beds interfinger and grade into one another laterally and vertically in short distances, the thinner beds in many places changing character or pinching out within a few hundred feet. The formations dip to the southeastward, the dip ranging from about 35 feet to the mile in the older formations to about 20 feet to the mile in the younger. In the outcrop-areas of the formations, and for considerable distances down the dip, the sediments are in general dominantly sandy. Far to the southeastward, in the direction of the Gulf, clay predominates.

Table 1--Estimated average daily pumpage in Houston and Pasadena, millions of gallons a day

Source	1930	1935	1937	1939	1940
Houston Water Department	25.8	24.5	25.2	27.2	29.0
Houston independent public water-supplies and industrial wells	14	14	16	16	17
Pasadena industrial wells	10	10	29	29	35
Totals, Houston and Pasadena	50	49	70	72	81

Table 2--Decline of water-levels in observation-wells in Houston District between 1937 and 1940, based on highest observed spring levels

Location	Number observation-wells	Average distance wells from paper mill, miles	Range of decline, feet	Average decline, feet
Wells screened opposite heavily pumped sands				
Vicinity of Pasadena	6	3-1/2	27.5 to 50.0	37.0
Eastern Houston	5	6	29.1 to 37.8	32.0
Northern Houston	2	11	27.0 and 35.1	31.0
Central and Western Houston	6	10-1/2	13.0 to 19.8	16.8
Locality west of Houston	3	15-1/2	12.2 to 17.4	15.5
Locality north of Houston	2	21	8.4 and 17.2	12.8
Wells screened opposite lightly pumped sands[a]				
Vicinity of Pasadena	2	5	13.0 and 13.0	13.0
Central and Western Houston	3	11-1/2	4.5 to 6.9	5.6

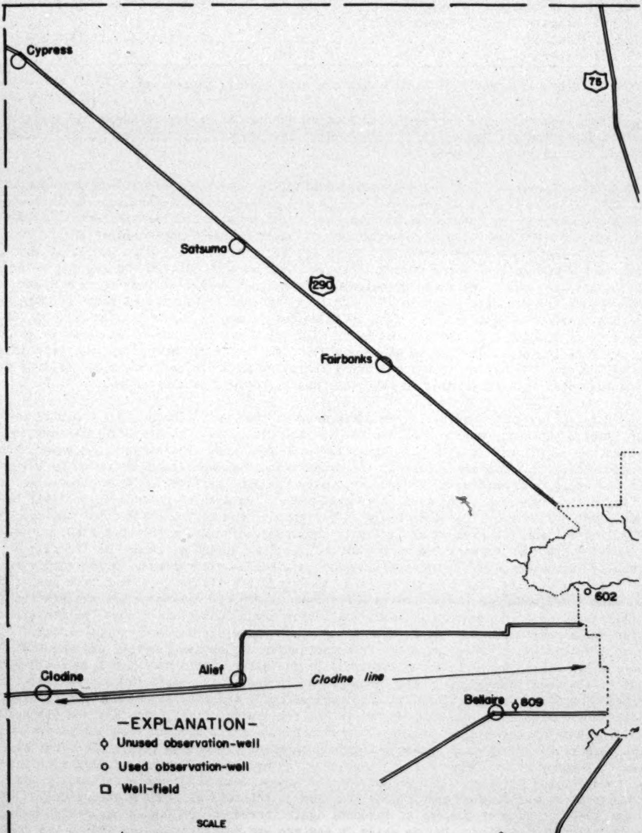
[a] These sands are indirectly connected with the more heavily pumped sands.

Pumpage--Nearly all of the water-supply of Houston and the adjoining Pasadena industrial area comes from approximately 225 wells. The estimated average daily pumpage during 1930, 1935, 1937, 1939, and 1940 is given in Table 1.

The outstanding feature of the pumpage record during the last ten years is the phenomenal increase in 1937 of about 19,000,000 gallons a day in the pumping rate at Pasadena--an increase of nearly 40 per cent over the total combined pumpage in the Houston and Pasadena areas in 1936. This was the result of the operation of three groups of wells by the Champion Paper and Fibre Company, which were brought into service about March 1, 1937. These wells were pumped at the rate of about 19,000,000 gallons a day during 1937, but only at about 16,000,000 gallons a day during 1938 and most of 1939. There was no material change in the rate of pumping from other wells in the Houston and Pasadena areas in 1937 and 1938, and the total rate of combined pumping in the two areas, therefore, was somewhat less in 1938 than it was in 1937. In the fall of 1939, however, the rate of pumping increased in the paper-mill wells and in a number of other wells in both areas, bringing the total in 1939 to about 2,000,000 gallons a day more than the total in 1937. In 1940 the rate of pumping in the two areas increased an additional 9,000,000 gallons a day, bringing the total rate of pumping in 1940 to about 81,000,000 gallons a day.

Decline of water-levels in wells--In the early days of Houston, flowing wells could be obtained by drilling practically anywhere within the Houston District. The artesian pressure in some localities was sufficient to raise the water 15 to 30 feet above the surface. However, in 1931 the artesian head in the greater part of the Houston and Pasadena areas, as shown by water-levels in unused wells, was between 50 and 80 feet below the land-surface, or from about sea-level to 30 feet below sea-level, the decline in head having averaged about four feet a year between 1920 and 1931. As a result of a decrease in the rate of pumping in these areas between 1931 and 1933, the maximum observed water-levels in the observation-wells showed a rise, on the average, of about 3-3/4 feet between the spring of 1931 and the spring of 1933. As the rate of pumping gradually increased between 1933 and 1936, the maximum levels recorded in the spring and early summer showed a decline, the average decline amounting to a little more than five feet for the period. When additional pumping at the rate of about 19,000,000 gallons a day was started at the paper mill in Pasadena about March 1, 1937, the levels began to decline almost immediately in observation-wells near Pasadena. By October 1, 1937, the water-levels had dropped about 45 feet in two observation-wells about two miles from the center of the new pumpage, and about 35 feet in a well 2-1/2 miles away. In more distant wells the water-levels declined less rapidly, the magnitude of the decline and lag in its transmission in most cases depending on the distance from the center of pumping at the paper mill. In some wells in the central and western parts of Houston and elsewhere several months elapsed before the decline resulting from this new pumpage was noticeable. From the latter part of 1937 to the corresponding period in 1938 the water-levels in the observation-wells near Pasadena remained constant or rose slightly. This was due to a decrease in pumping at the paper mill. In observation-wells at Houston, and west and north of the City, however, the decline continued during 1938 and in some wells was more than it was in 1937, although there had been no appreciable increase in the rate of pumping at Houston. During 1939 and 1940 the rate of pumping at Pasadena again increased and the water-levels there declined rapidly and persistently. In the wells in eastern and northern Houston and in the area north of Houston the decline in 1939 was more than it was in 1938, and the rate of decline increased in 1940. A part of the increase in the rate of decline in Houston in 1939 and 1940, however, was due to increased pumpage from the municipal wells and a few privately-owned industrial wells in Houston. The decline in the artesian head in the Houston District between the spring of 1937 and the spring of 1940 is given in Table 2. The hydrographs of seven of these wells are shown in Figures 4, 5, and 6. The approximate altitudes of water-levels in observation-wells that draw from the heavily pumped sands are shown by contours in Figure 2.

Application of coefficients of transmissibility and storage: Is the use of average figures justified?--The values for the coefficient of permeability determined by Jacob from pumping tests at the municipal well-fields range from 100 to 530 and average about 300. (The coefficient of permeability used in this paper is uncorrected for water-temperature, and is represented by k in the paper by C. E. Jacob contained in these Transactions.) The thickness of sands in which the tests were made ranges from 157 to 591 feet and averages about 300 feet. In 14 of the


Cypress
75
Satsuma
290
Fairbanks
602
Alief
Clodine
Clodine line
Bellaire
809
-EXPLANATION-
Unused observation-well
Used observation-well
Well-field
SCALE
0 1 2 3 4 5 MILES
90

tests, his values for the coefficient of storage range from 0.00017 to 0.00108 and average about 0.0005. When these figures are adjusted to the total thickness of the beds, estimated as about 600 feet, the average coefficient of transmissibility becomes 300 x 600 or 180,000 and the average coefficient of storage, which is considered approximately proportional to the thickness of the aquifer, becomes 0.0005 x 600/300 or 0.001.

It is believed that the only way to make a practical application of the coefficients obtained from the pumping tests to the Houston District as a whole is to use averages of the figures determined for transmissibility and storage. In support of the use of average figures for the District as a whole it can be said that the wells in which the pumping tests were made are spaced over a wide area, 50 square miles or so, and penetrate nearly all of the principal water-bearing sands. A logical argument against the use of the averages is the wide range in the

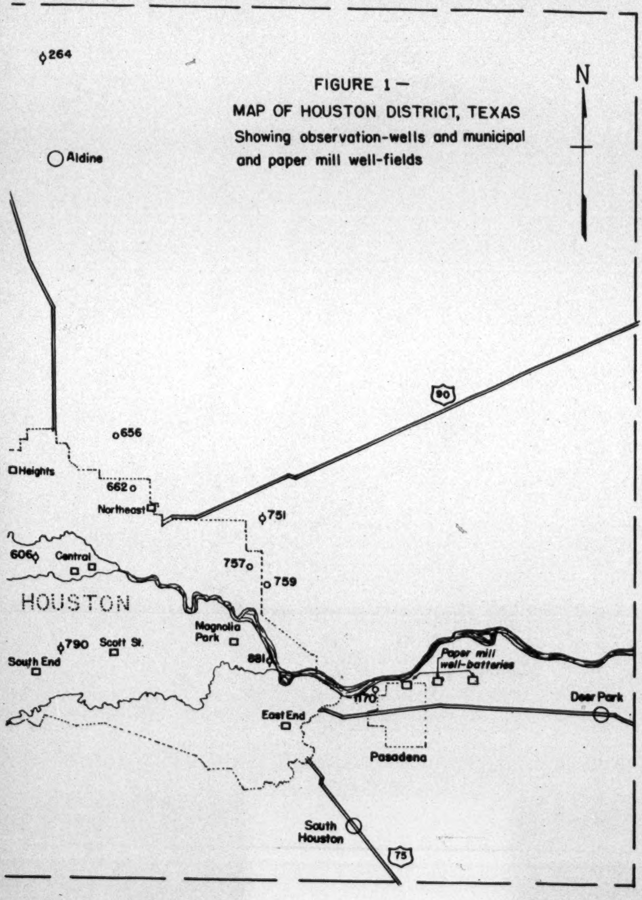


FIGURE 1 —
MAP OF HOUSTON DISTRICT, TEXAS
Showing observation-wells and municipal and paper mill well-fields
N
264
Aldine
90
656
Heights
662
Northeast
751
606
Central
757
759
HOUSTON
Magnolia Park
790
Scott St.
South End
881
Paper mill well-batteries
1170
Deer Park
East End
Pasadena
South Houston
75

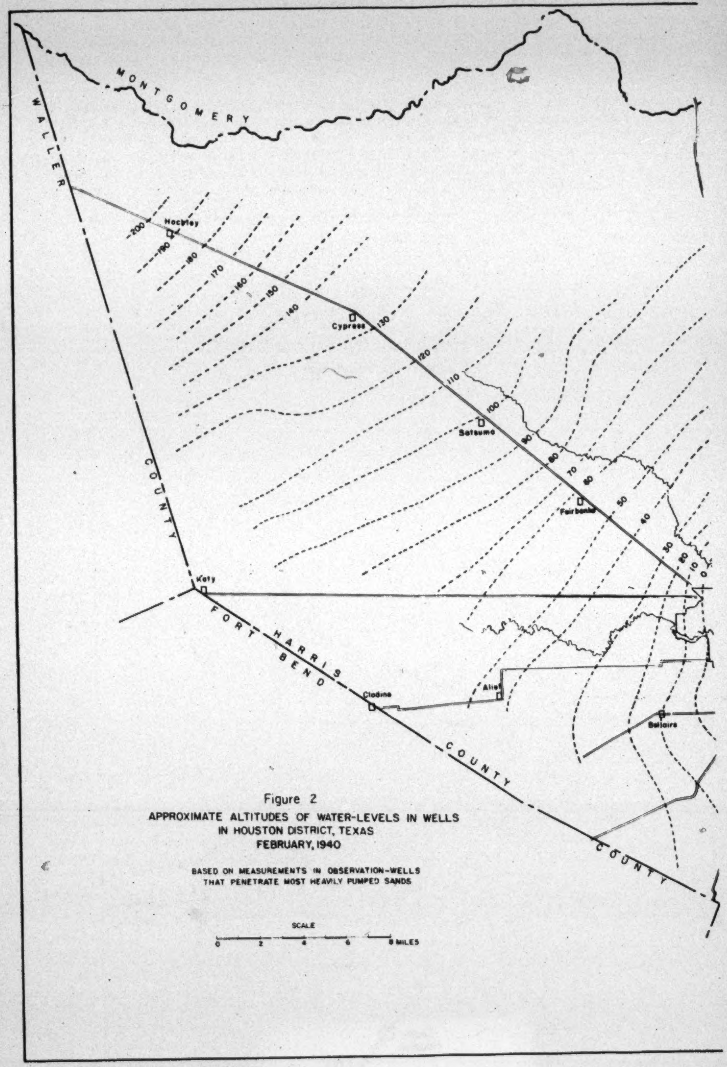

MONTGOMERY
WALLER COUNTY
FORT BEND COUNTY
HARRIS COUNTY
Hockley
Cypress
Satsuma
Fairbanks
Katy
Clodine
Alief
Bellaire
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
SCALE
0
2
4
6
8 MILES

Figure 2
APPROXIMATE ALTITUDES OF WATER-LEVELS IN WELLS
IN HOUSTON DISTRICT, TEXAS
FEBRUARY, 1940

BASED ON MEASUREMENTS IN OBSERVATION-WELLS
THAT PENETRATE MOST HEAVILY PUMPED SANDS

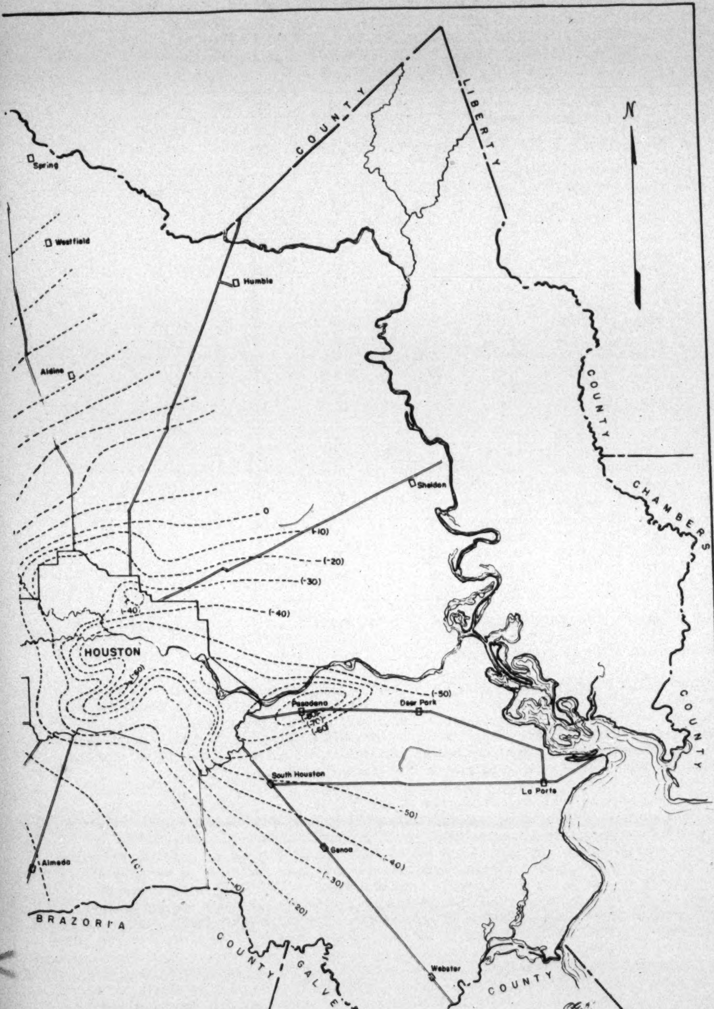

N
Spring
Westfield
Humble
Aldine
Sheldon
HOUSTON
Pasadena
Deer Park
South Houston
La Porte
Genoa
Almeda
Webster
COUNTY
LIBERTY
COUNTY
CHAMBERS
COUNTY
BRAZORIA
COUNTY
GALVESTON
COUNTY
0
(-10)
(-20)
(-30)
(-40)
(-40)
(-50)
(-50)
(-80)
(-70)
(-60)
50)
(-40)
(-30)
(-20)
(-10)
(0

Table 3--Actual decline of water-levels in observation-wells, 1937 to 1939, based on highest measurements in spring, and theoretical drawdown caused by paper-mill pumpage as computed from non-equilibrium formula, assuming coefficient of transmissibility as 180,000 and coefficient of storage as 0.001

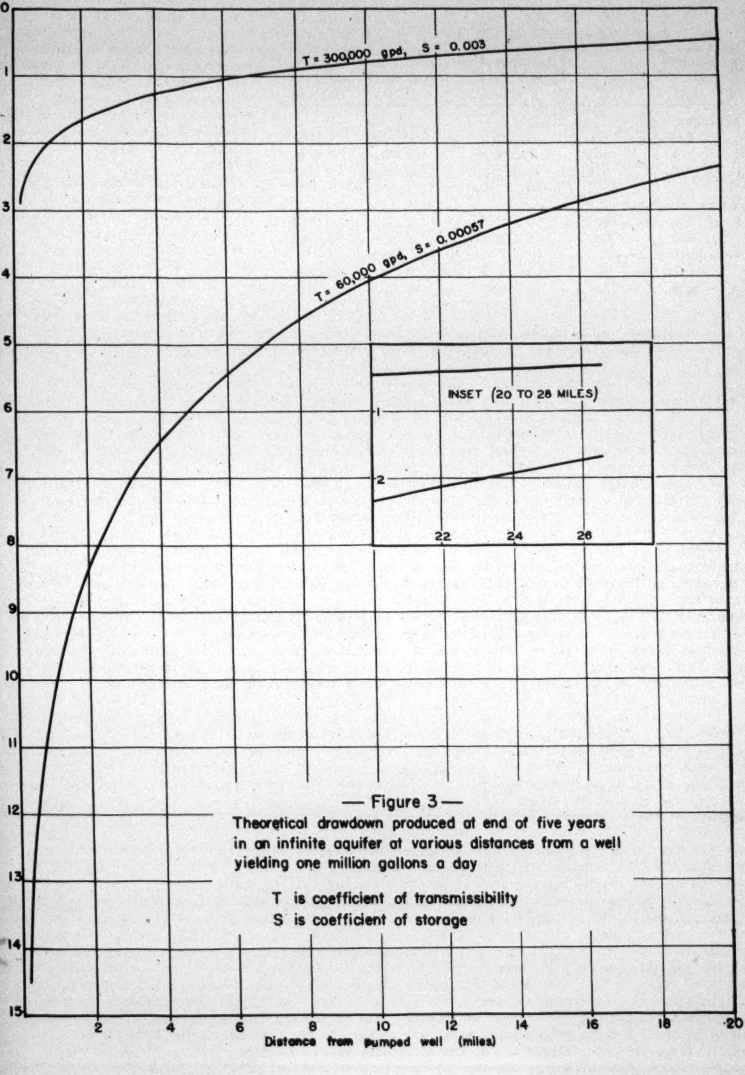
Observation-well	Distance from paper mill, miles	Depth, feet	1 year (1937-38)		2 years (1937-39)	
			Computed draw-down, feet	Actual decline, feet	Computed drawdown, feet	Actual decline, feet
[a] 1170	1-1/2 W	836	50	31	47	30
1176	2 NW	1,134	44	29	42	32
1209	4-1/2 S	650±	30	6	30	11
881	4-1/2 W	650	30	17	30	23
[a] 890	4-1/2 W	1,284	30	22	30	--
[a] 878	5 W	905	28	25	29	29
886	5 W	540	28	7	29	8
759	5-1/2 NW	569	26	16	27	22
757	6-1/2 NW	676	24	13	26	20
751	7 NW	540	23	12	24	19
868	7 W	694	22	1	23	5
[a] 853	9-1/2 W	650±	18	4	20	11
[a] 680	9-1/2 NW	1,280	18	13	20	11
662	10 NW	834	17	12	19	19
[a] 790	10-1/2 W	606	16	+ 1	18	9
[a] 619	10-1/2 NW	625	16	2	18	11
656	11-1/2 NW	665	15	11	17	17
820	11-1/2 W	310	15	1	17	4
606	12 NW	575	14	5	17	12
604	12-1/2 NW	340	13	1	16	0
602	13-1/2 W	864	12	8	15	13
804	14-1/2 W	650±	11	6	14	12
783	15-1/2 W	350±	10	3	13	8
809	15-1/2 W	1,100±	10	6	13	10
264	21 NW	950±	7	12	9	14

[a] Water-level materially affected by local pumping.

figures obtained from the individual tests.

The only available method in the Houston District of evaluating Jacob's coefficients of transmissibility and storage is by the use of the non-equilibrium formula [C. V. Theis, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage, Trans. Amer. Geophys. Union, pp. 519-524, 1935], which Jacob used in their determination. It must be assumed that the use of the formula is valid, although this has not yet been proved in an area such as the Houston District.

An effort was made to evaluate the average of the coefficients of transmissibility and storage determined by Jacob, by using the non-equilibrium formula with the average coefficients. By means of the formula drawdowns were computed which theoretically should have occurred in a number of observation-wells at periods of one and two years after pumping was begun by the paper mill in 1937. These theoretical drawdowns, together with the actual declines in water-levels, are given in Table 3. The wells are arranged in Table 3 from top to bottom in the order of their distance from the paper mill. The ones which were probably affected by changes in the yearly rate of local pumping are indicated by a foot-note. The Table shows that, except for Well 264, the computed drawdown at the end of one year is much more than the actual decline, the difference between the two, in most cases, being large in comparison to the actual decline. In some of the wells the computed drawdown is several times as much as the actual decline. In others it is only a little different from the decline. In all of the wells, except four, the computed drawdown at the end of two years is also larger than the actual decline, but the difference between them, while still of considerable magnitude, is not as large in proportion to the actual decline as at the end of one year. It will be seen that wells at approximately the same distance from the paper mill had widely different declines during the two-year period. Where the observation-wells are not affected by variations in local pumping, these differences



— Figure 3 —

Theoretical drawdown produced at end of five years in an infinite aquifer at various distances from a well yielding one million gallons a day

T is coefficient of transmissibility

S is coefficient of storage

Table 4--Coefficients of transmissibility and storage determined by the Theis graphical method from two-year drawdowns produced by the paper-mill pumpage

Observation-well	Depth, feet	Distance from paper mill, miles	Coefficient transmissibility	Coefficient storage
East Houston				
881	650	4-1/2 W	130,000	0.0054
759	569	5-1/2 NW	133,000	0.0046
757	676	6-1/2 NW	131,000	0.0045
751	540	7 NW	125,000	0.0041
North Houston				
662	834	10 NW	112,000	0.0021
656	665	11-1/2 NW	119,000	0.0021
West Houston				
602	864	13-1/2 W	173,000	0.0016
809	1,100±	15-1/2 W	196,000	0.0019

can only be explained by the fact that the wells are of different depths, or located in different directions from the paper mill. The record on the whole, therefore, seems to indicate that the individual beds vary widely in transmissibility, and some of the beds are much more closely interconnected than others.

In order to visualize the range in drawdown covered by the coefficients of transmissibility and storage determined from the pumping tests, the non-equilibrium formula was used to compile data for the curves shown in Figure 3. Curve A was computed from the maximum adjusted coefficients of transmissibility and storage, and curve B from the minimum. The drawdown at every point on curve B is about five times the drawdown at the corresponding point on curve A.

An attempt was made to compute the actual coefficients of transmissibility and storage which exist between the paper-mill wells and the observation-wells by the Theis graphical method, using the non-equilibrium formula. Only eight wells out of the 25 observation-wells, for which good records are available, were found to have hydrographs showing declines in water-level which would conform to the theoretical curve so as to give reasonable results. There were no material changes in the yearly rate of local pumping near any of the eight wells during 1937 and 1938. Three of these hydrographs are shown in Figure 4. In applying the Theis graphical method it was assumed that the pumpage was evenly distributed throughout all the sands, that the sands are interconnected and act as one large aquifer, that the pumping at the paper mill was at a uniform rate of 17 million gallons a day, that the pumpage was all from one large well at the approximate center of pumping, and that the effect of a constant head at the outcrop could be neglected. Table 4 gives the coefficients of transmissibility and storage that were computed by this method. The wells in Table 4 are subdivided into three groups, according to their location and distance from the paper mill. It will be seen that the coefficients of both transmissibility and storage computed for the individual wells are closely comparable in each group, but the averages for the different groups vary widely. The average of all the coefficients gives 140,000 for the coefficient of transmissibility and 0.0033 for the coefficient of storage. The average for transmissibility is not greatly different from the adjusted average of Jacob's pumping-test results, while the average for storage is approximately three times his adjusted average.

In obtaining the coefficients of transmissibility and storage from the eight wells mentioned, and in computing the drawdowns in Table 3, the assumption least justified is that all the heavily pumped sands in the Houston District may be considered as one aquifer. Other sources of small error are (1) the lack of accurate data concerning the trend the water-levels would have taken if the paper-mill wells had not been pumped, (2) the difficulty of accurately determining the location and extent of the outcrops of the sands, and (3) the assumption that the pumpage at the paper mill was at a uniform rate from one large well.

As has been mentioned, the hydrographs of only eight observation-wells out of 25 conform reasonably with a theoretical curve and can be used to determine coefficients of transmissibility and storage by the Theis graphical method. The lack of conformity in six of the wells probably is due to the effect of changes in the yearly rate of pumping from nearby wells or from the well itself, and in two of the wells, which are near the paper mill, to the effect of changes in the rate of pumping at the mill. The effects of these changes are illustrated by the hydrographs of wells 790 and 1170 in Figure 5. Well 790 was pumped until the fall of 1936 or winter of 1936-37, and then was abandoned. Its hydrograph for 1937 apparently shows the combined effects of recovery from the well's own cone of depression and the drawdown caused by the pumping at the paper mill which was started in the spring of 1937. Well 1170 is a used well about 1-1/2 miles from the paper mill's center of pumping. Its hydrograph illustrates the effect of changes in the rate of pumping by the paper mill, and changes in the rate of pumping from the well itself. These records are examples of the difficulty which occurs in obtaining a record for a long period of time which may possibly conform to a theoretical drawdown produced by a given increase in pumping.

The nine remaining observation-wells whose hydrographs do not reasonably conform to a theoretical curve were not materially affected by changes in the yearly rate of local pumping during 1937 and 1938, so far as is known. Wells 264 and 606, whose hydrographs are shown in Figure 6, are examples. The record of Well 264, in contrast to theory, shows that over half the decline since the spring of 1937 occurred during a comparatively brief period between 5-1/2 and 7-1/2

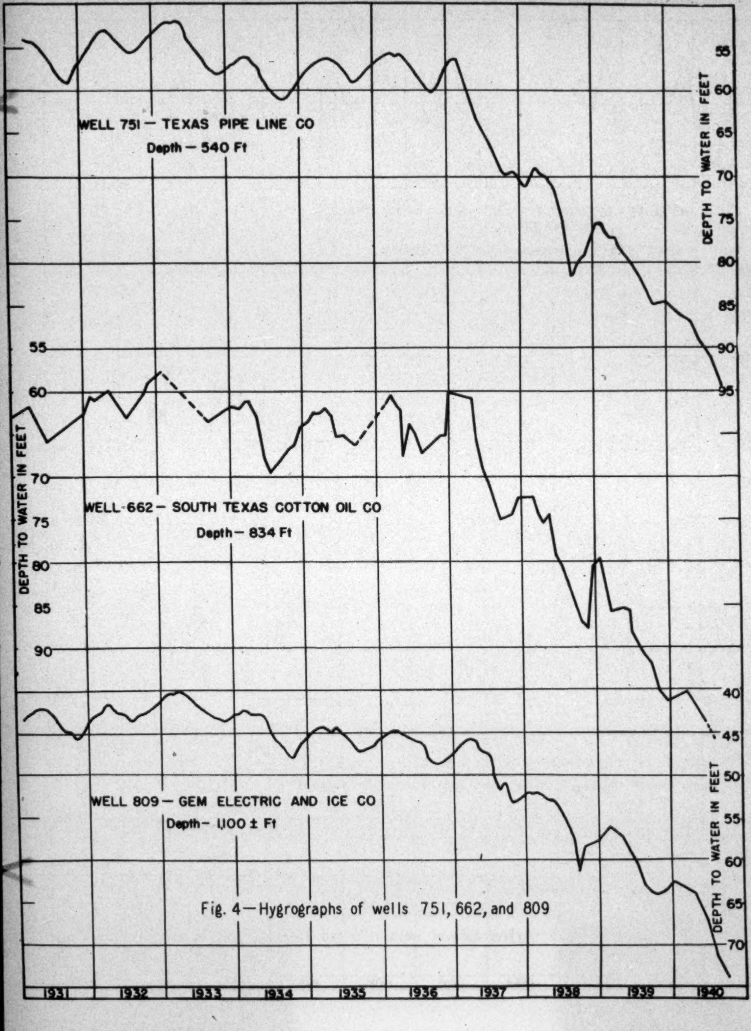


Fig. 4—Hygrographs of wells 751, 662, and 809

months after the paper mill began pumping. The hydrograph of Well 606 gives quite a different picture, showing much less decline during 1937, the first year after pumping at the paper mill was started, than during each succeeding year. These records illustrate how difficult it is in the Houston District to predict water-level changes with given changes in pumping rates, even though long-term records in nearby observation-wells are available.

Computations of inflow and withdrawal from artesian storage--The rate of inflow into the

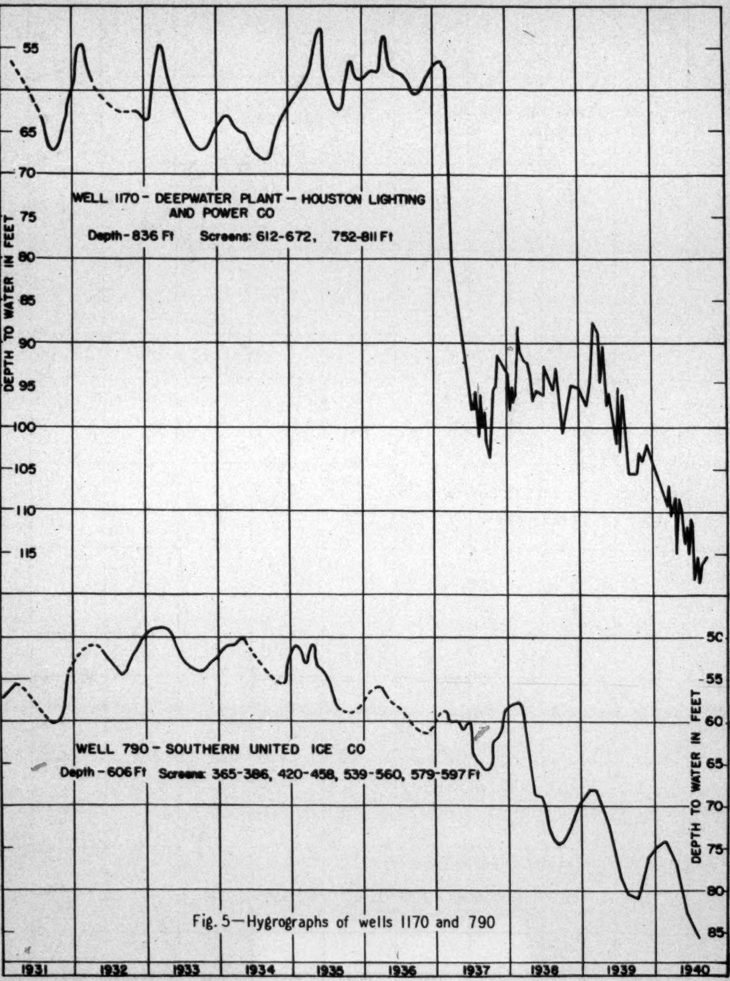


Fig. 5—Hygrographs of wells 1170 and 790

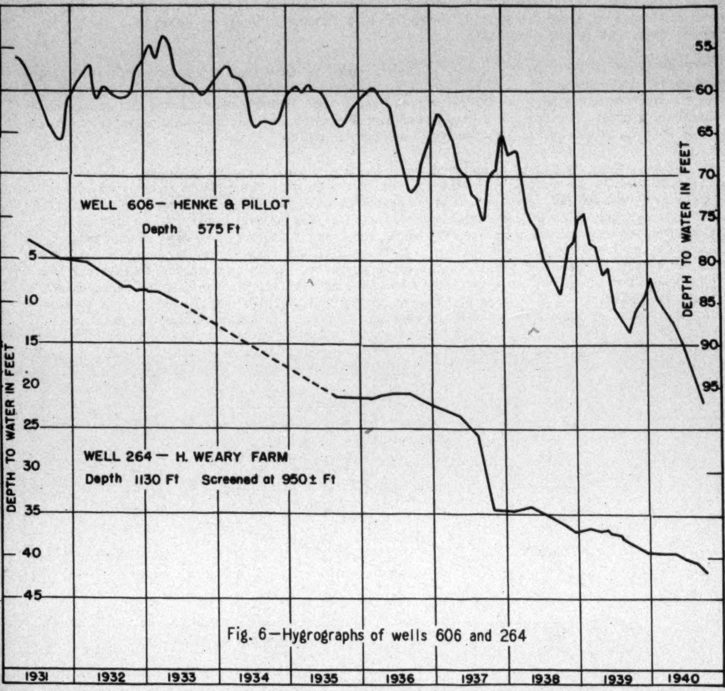


Fig. 6—Hygrographs of wells 606 and 264

Houston and Pasadena areas in February, 1940, may be calculated according to Darcy's law, which states that the rate of flow of water through a given cross-sectional area of sand is directly proportional to the hydraulic gradient and to the permeability of the sand. The approximate hydraulic gradient in the most heavily pumped sands of the Houston District in February, 1940, is shown in Figure 2. In this Figure the contour at ten feet below sea-level is chosen as the line along which the rate of inflow to the Houston and Pasadena areas can be most readily and accurately determined. It is estimated that the length of this line is approximately 45 miles, the average hydraulic gradient across the line about ten feet to the mile, the average thickness of the sands about 600 feet, and the average coefficient of permeability (as determined from Jacob's pumping-test results) about 300. The rate of inflow in February, 1940, is thus computed as 180,000 × 45 × 5280 × 10 divided by 5280, or 81,000,000 gallons a day, which is probably at least 10,000,000 gallons a day in excess of the daily rate of pumping at that time.

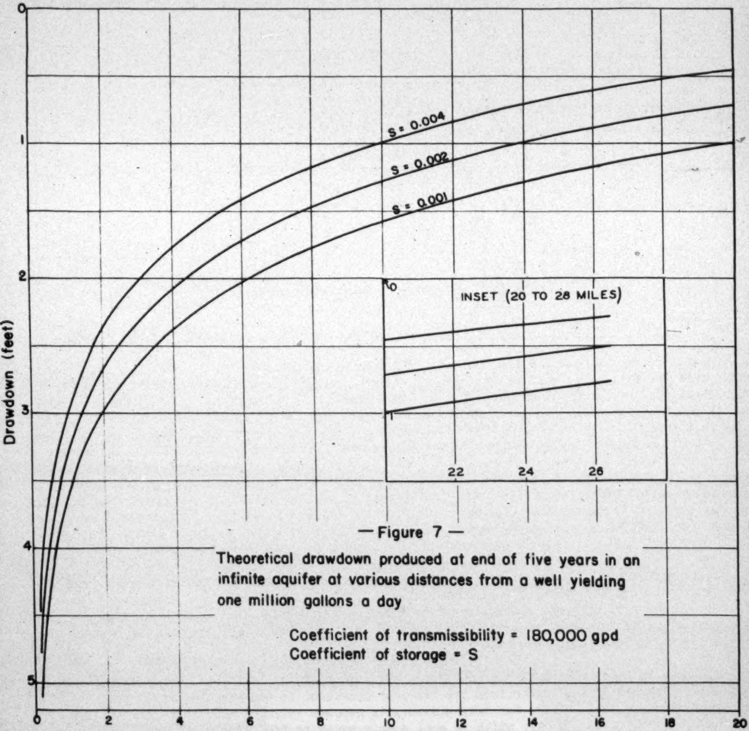
Assuming that the average coefficient of storage is 0.001 (Jacob's adjusted average) and that the average decline during a period of one year--from February, 1939, to February, 1940--was ten feet over an area of about 300 square miles within the minus ten-foot contour in Figure 2, the amount of water taken out of artesian storage in this 300 square-mile area during the one-year period is calculated to have been about 2,000,000 gallons a day.

If a mean is taken between Jacob's average coefficient of transmissibility and the average coefficient obtained by the writer from the two-year drawdowns in the eight selected wells previously mentioned, the figure for transmissibility becomes 160,000, and the rate of inflow becomes 72,000,000 gallons a day, which is more nearly equal to the rate of pumping in February,

1940. The use of the average of the two coefficients of storage gives a rate of withdrawal from artesian storage of 3,500,000 gallons a day for 1939. These figures were used in a recent progress-report on the Houston District.

It is believed that these figures, although rough, do show that withdrawal from storage in the heavily pumped areas is relatively small in comparison with the total amount of water pumped. However, since declines have actually occurred over a much larger area than the 300 square miles considered, a greater proportion of the water pumped would be found to be withdrawn from artesian storage if computations could be made for the entire District.

Application of the non-equilibrium formula in determining relative drawdowns--The non-equilibrium formula has tentatively been applied in the Houston District to make estimates of the relative drawdowns at given points with various hypothetical changes in pumping rates. The installation of new wells at considerable distances from the present center of pumping is being contemplated to meet increased demands for water and check further development of the present extensive water-level depressions. It is important to locate these wells so that they will have a minimum effect on the water-levels in the areas where the levels are already excessively low, both to keep down the cost of pumping and to keep the possibilities of salt-water encroachment as small as possible. In a program of exploratory drilling carried out by the City of Houston during the summer of 1939, nine test-wells were put down west of Houston along the Houston-

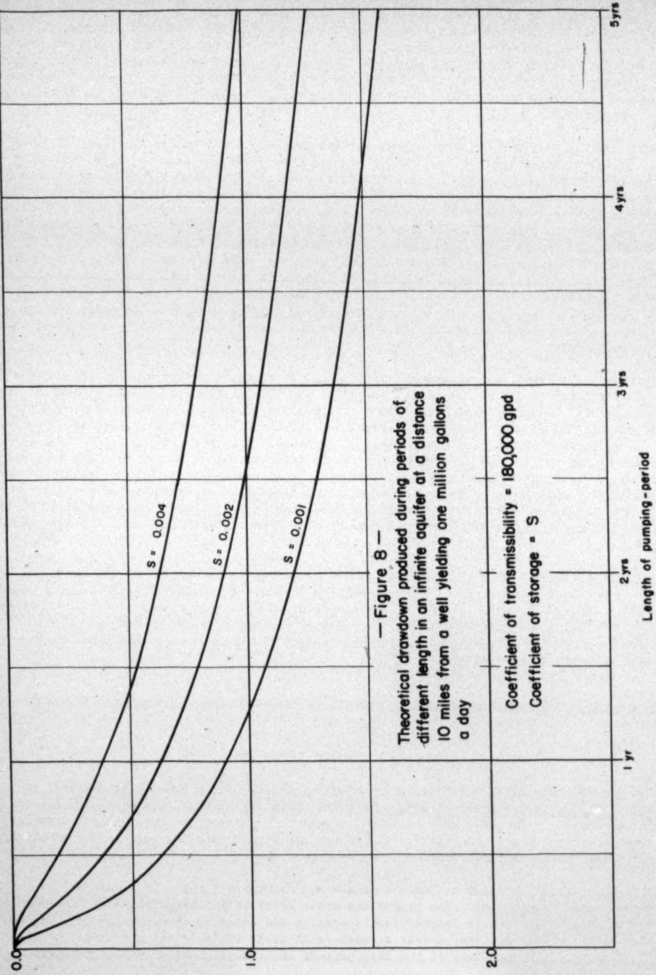


— Figure 7 —

Theoretical drawdown produced at end of five years in an infinite aquifer at various distances from a well yielding one million gallons a day

Coefficient of transmissibility = 180,000 gpd
Coefficient of storage = S

Clodine Road. These wells show that there is an average of 600 feet of water-bearing sands between the surface and a depth of 1,500 feet along the line of test-wells from the western city-limits of Houston to Clodine. The location of this line is shown in Figure 1. It has been proposed that new wells be drilled and pumped along this line and that the rates of pumping from Pasadena industrial wells and the Houston well-fields be decreased. Tentative estimates of the relative merits of various arrangements of the new wells and changes in pumping involved in this readjustment have been made by the use of the non-equilibrium formula.



— Figure 8 —

Theoretical drawdown produced during periods of different length in an infinite aquifer at a distance 10 miles from a well yielding one million gallons a day

Coefficient of transmissibility = 180,000 gpd
Coefficient of storage = S

Possible explanation of difference between coefficients of storage determined from Jacob's tests and those determined from the paper-mill drawdowns--As has been stated, the average coefficient of storage determined from a record of declines in water-levels over a period of two years following the start of pumping at the paper mill is more than three times the adjusted average of the coefficients determined by Jacob. This seems to indicate that the time element involved in a decline makes a great difference in the coefficient of storage which is obtained. It is now generally recognized that the clays above and below a water-bearing sand and interbedded with it give up considerable water when the artesian head within the sand is lowered. Probably they continue to give up water for a long time after the drop in head has occurred. It is possible, moreover, that the sands also become more and more compressed and continue to release water for a long time after the drop occurs. The values obtained for the coefficient of storage seem to show that probably one or both of these factors have caused the release of a much larger quantity of water from storage over a period of two years in the Houston and Pasadena pumping areas than was calculated to be released using the coefficients obtained by Jacob in tests of a few hours' duration.

A second possibility for the discrepancy between the determinations is that Jacob's tests were made in well-fields where the head had fluctuated many times through the range recorded, whereas the water-levels in observation-wells used to evaluate his results were lower than they had ever been before, and therefore were declining through that range in head for the first time. It has been found in some cases that sands and clays, which are under a constant load and which have been compressed by a reduction in internal hydraulic pressure, do not expand to their original volume when the pressure is increased to its original amount. Therefore, after water is once removed from storage within a sand and its adjacent clay-beds as a result of a decline in artesian head, the beds may not again take into storage, with a comparable rise in head, as much water as was released with the decline. If so, they will also not release as much water with a second decline as with the first. If this is true in the Houston District, the range through which a change in water-level is taking place may also be one of the determining factors of the coefficient of storage.

Differences in theoretical drawdowns caused by different coefficients of storage--The curves in Figure 7 give the theoretical drawdown produced at the end of five years in an aquifer of infinite areal extent at various distances from a well yielding 1,000,000 gallons a day, computed by the non-equilibrium formula, using a constant coefficient of transmissibility of 180,000 and coefficients of storage of 0.001, 0.002, and 0.004. These curves show that, in proportion to the magnitude of the total drawdown, the difference in drawdown near a pumped well due to a difference in the coefficient of storage is not very much, but that the proportional difference becomes progressively more as the distance from the well increases. For example, at a distance of 1,000 feet from the pumped well, the drawdown computed from a coefficient of storage of 0.001 is only about 14 per cent greater than the drawdown computed from a coefficient of 0.004--whereas, at a distance of 20 miles, it is 118 per cent greater.

The curves in Figure 8 show the range in theoretical drawdown (computed by the non-equilibrium formula) produced during different periods of time in an aquifer of infinite areal extent at a distance of ten miles from a well yielding 1,000,000 gallons a day, using a coefficient of transmissibility of 180,000 and coefficients of storage of 0.001, 0.002, and 0.004. These curves show that the proportional difference between the drawdowns becomes less as the length of the pumping period increases.

U. S. Geological Survey,
Houston, Texas

DISCUSSION OF PAPERS BY MESSRS. JACOB AND GUYTON

M. KING HUBBERT (New York, New York)--The papers by Messrs. Jacob and Guyton may very well constitute a milestone in the progress of ground-water hydrology in that they represent one of the earliest extensive field-tests wherein it was sought to determine the significant parameters of the aquifer under transient conditions. The parameters sought were the coefficient of storage and the coefficient of transmissibility.

The work upon which the paper by Jacob is based was conducted first. This was done during a field-season of but four months. The conditions under which it was conducted were far from ideal since the wells used were in intermittent operation and could not arbitrarily be shut down for more than brief periods of time--a week at most--with other wells in the same group still operating. Because of the shortness of the time-periods the transient effects from a single well were only observable at other nearby wells of the same group at distances of a few hundreds of feet away. Tests of a similar kind, however, were repeated at most of the well-groups in the District, giving a large number of independent determinations of the two parameters for different points of the area. These values may thus be regarded as representing a sampling procedure at a number of points.

The values of the parameters thus obtained agree reasonably well among themselves and give, for the regions, average values (based upon 600-foot thickness of aquifer) of approximately: (1) Coefficient of transmissibility, 180,000; (2) coefficient of storage, 0.001.

Guyton took the foregoing results obtained from short-time and short-distance measurements and checked them against observations involving large distances and long times. For this he employed as his source of disturbance the well-group at the paper mill at Pasadena. Hydrographs over a period of two years were obtained from 25 observation-wells at distances ranging from 1-1/2 to 21 miles. Of these he reports that 17 were too anomalous to use. The remaining eight showed drawdowns comparable to what was predicted from the non-equilibrium formula. Independent computations from these gave coefficients of transmissibility in substantial agreement with the value obtained by Jacob, but average coefficients of storage of three to four times the value of Jacob. Of the 17 anomalous wells, the behavior of eight was accounted for by local disturbances; the other nine remained unaccounted for.

Accepting these results at face value, the question that confronts us is whether the two sets of data thus presented are seriously at variance with one another. There is also a question of their relative reliabilities, of the extent that they do not agree, and of what are the various possible sources of the disagreement?

The basic assumption upon which the theory underlying these computations was based is that the aquifer is uniform in all respects horizontally to unlimited distances. An auxiliary assumption of less importance than the first named is that the upper and lower bounding-surfaces of the aquifer are completely impervious to the passage of water.

If the first of these assumptions is entirely satisfied in the field, then from any single point-disturbance the effect should be the same at the same distance in all directions (horizontally). Conversely, if only a single point-disturbance is operative, and the effects at equal distances are not the same when all other factors are the same, then this may be regarded as direct evidence that the assumption of horizontal (or radial) homogeneity has been violated. In the absence of other disturbing factors, the nine anomalous wells appear to indicate the existence of horizontal inhomogeneities in the aquifer.

Another discrepancy that may affect Guyton's computations is his assumption that the wells at Pasadena may be considered as one large well at the center of the group. According to the map (Fig. 1) these wells occur in three groups at intervals of one mile in a nearly east-west direction. The drawdown due to these wells, as shown on the contour-map (Fig. 2), is not a circular depression but a highly elliptical one with the long axis bearing about north 70° east. Even if the aquifer were ideally homogeneous, the drawdown at different observation-wells would be a function of the azimuth as well as of the radius from the center of the group at Pasadena. With no allowance for this fact, the application of the non-equilibrium formula to wells in different directions would give different values for the parameters sought.

Again, it cannot be assumed that, because the pumping well and the observation-well are several miles apart, the values obtained by computation in this manner are average values of the parameters for the region between the two wells. Any local inhomogeneity or other disturbing factor at or near the observation-well will affect the results far more than corresponding effects, say, half way between the two wells. What are obtained in this manner are not average regional values for the parameters, but highly localized apparent values. This is very similar to what is observed in electrical-resistivity measurements. In these measurements computations are made on the basis of a theory which is valid only for a volume whose resistivity is constant. When applied to an inhomogeneous medium it was first erroneously supposed that the values so obtained were average values for the region. It soon was recognized, however, that this was far from the case, and that the results were only "apparent" values whose variations with position of observation were indicative of local inhomogeneities, and not even a measurement of those.

In view of these several facts, it is my opinion that the values of the parameters obtained by Guyton are considerably less reliable as average regional values than those obtained by Jacob. On the other hand, as Guyton suggests, there may actually be a time-factor in the coefficient of storage which would produce a larger value in a drawdown of two years' duration than would be perceptible from observations of only a few days' duration. Flow of water into the aquifer across its upper and lower boundaries might conceivably produce such an effect also. Until more and better data become available, however, such questions must remain more or less speculative.

It seems to me, therefore, that the results presented in these two papers, rather than being in disagreement or contradictory, actually complement each other very well. Each set of observations really throws light upon different properties of the region under investigation. Furthermore, the two types of results are not to be unexpected for a region of this size.

The ultimate practical object of such work is to obtain data by means of which future addition to the water-supply plant for the area can be given the optimum location and rate of operation. The alternative to investigations along the general lines of the present ones seems to be a reversion to blind guess-work. Considering its brevity, there is no reason for concern if the present work may have raised questions that are still unanswered. Such questions rather are indicative of the fact that additional work in the District, of the same calibre as this, would be informative.

FACTORS PRODUCING A NINE-YEAR DECLINE IN GROUND-WATER LEVELS IN SCOTT COUNTY, KANSAS

Herbert A. Waite

(Published with the approval of the Director, Geological Survey, U. S. Department
of the Interior, and of the Director of the Kansas Geological Survey)

In the south-central part of Scott County, Kansas, there is an area of shallow water-table in which the ground-water levels have declined steadily since 1932 (Fig. 1). In this area water has been withdrawn from wells for irrigation in increasing amounts during the last decade and the precipitation has been considerably below normal for the last seven years. Thus, the problem of interpreting the downward trend of the water-table has been complicated by the presence of two competent causes.

Figure 1 shows that Well 1 had a net decline in water-level during the period of record (October 1931 through December 1940) of 4.43 feet, which represents an average annual decline of 0.55 foot. The graphs in Figure 1 appear to show a direct correlation between fluctuations of water-level in Well 1 and the cumulative departure from normal precipitation, and suggest that the subnormal precipitation might be entirely responsible for the lowering of the water-level in the Well and in other wells in the area. The Figure also shows, however, that from year to year the irrigated acreage in the shallow-water area has increased steadily, culminating with a total of approximately 17,200 acres in 1940. Based upon a compilation of the estimated pumpage at each of the irrigation-wells in the area, a total of approximately 17,700 acre-feet of water was pumped from irrigation-wells in the shallow-water area in 1940. The present paper discusses the relative importance of drought and pumping in producing the decline of water-levels. Additional data will be given in a report on the geology and ground-water resources of Scott County, which is now in preparation.

An investigation of Scott County was made in 1939 and 1940 by the Federal Geological Survey and the Kansas Geological Survey, in cooperation with the Division of Sanitation of the Kansas State Board of Health and the Division of Water Resources of the Kansas State Board of Agriculture. The investigation was under the direction of S. W. Lohman, Federal Geologist-in-Charge of ground-water investigations in Kansas, and was part of a larger program of comprehensive ground-water investigations in Kansas that was begun in July, 1937. The Division of Water Resources made available the water-level records of two wells in Scott County that have been equipped with automatic water-stage recorders for several years [Water levels and artesian pressure in observation wells in the United States in 1939, U. S. Geol. Surv. W.-S. Paper 886, pp. 187-194, 1940; Water levels and artesian pressure in observation wells in the United States in 1940, U. S. Geol. Surv. W.-S. Paper in preparation].

The part of the decline in water-level in Well 1 that has been caused by a mounting deficiency in precipitation and the part that has resulted from the effects of pumping may be determined approximately by comparing the water-levels in the heavily pumped part of the area with those in other parts of Scott County where the water-level is only slightly affected by pumping. This can be done by comparing the configuration of the water-table on a map showing contours of the water-table in different parts of the area and by comparing the long-term fluctuations of water-levels in wells in the different localities.

The contours on the map (Fig. 2) show that in general the water-table beneath Scott County slopes eastward and that in the area of the heaviest pumping, about seven miles southwest of Scott City, a cone of depression has been established. The area of heavy pumping includes about eight square miles and is approximately delineated by the closed 2,910-foot contour-line. Well 1 is about 1-1/2 miles south of the southern boundary of this area of heavy pumping. Most of the pumping is from wells that tap water in the Ogallala formation at depths from about 60 to 160 feet and which yield from 500 to 2,000 gallons a minute.

The water-table in and near the area of heavy pumping stands from about 20 to 90 feet below the land-surface, in contrast to surrounding areas in which the water-table stands from about 90 to 160 feet below the surface. In general, the water-levels in wells in semi-arid regions fluctuate very little where the water-table is deep, and the effect of variations in precipitation is usually rather evenly distributed over broad areas. Thus, in parts of the County lying outside of the area of heavy pumping, where the water-table is deep, the contours of the water-table in general should be rather uniform and their configuration should remain about the same, even though they might shift progressively eastward or westward as a result of variations in recharge. Figure 2 shows that the contours in the vicinity of the heavily pumped area are not uniformly spaced and that undoubtedly their configuration has been altered from that which they originally had. This is indicated by the cone of depression enclosed by the 2,910-foot contour and by the bunching of the contours up-gradient from the heavily pumped area--the steeper gradients resulting from the extension of the cone of depression. Furthermore, the effects of pumping are suggested by the area of relatively flattened gradients just east of the heavily pumped area, a part of which effect has been caused by pumping and a part doubtless by heavy recharge in the vicinity of the terminus of Whitewoman Creek. It may be concluded, therefore, that a part of the decline in water-level in Well 1 has been caused by pumping.

The magnitude of the lowering of the water-level caused by pumping in the heavily pumped area can be estimated by straightening out the 2,920-foot contour from a point about two miles south of Scott City to a point about a mile west of Well 1, and projecting it across the heavily pumped area. By so doing, declines in water-level ranging from about 10 to 16 feet in the heavily pumped area are indicated. That the declines are of this general order of magnitude is confirmed by miscellaneous measurements that are available of the water-levels in three wells in

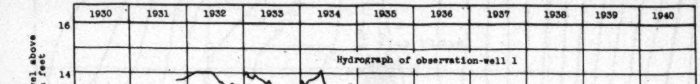


Fig. 1--Hydrograph of observation-well 1 in the Scott County shallow-water area, the cumulative departure from normal precipitation at Scott City, and the acreage irrigated from wells in the shallow-water area (Water-level record and irrigated acreage furnished through the courtesy of the Division of Water Resources, Kansas State Board of Agriculture) the heavily pumped area. This method, however, cannot be used to determine accurately how much of the lowering in the water-level of Well 1 was caused by pumping and how much was caused by deficient precipitation. During the period April 17, 1937, to February 15, 1941, the water-levels in the three wells had net declines ranging from 12.3 to 15.8 feet. Declines of this magnitude in the heavily pumped area are also reported by many drillers and owners of wells. Similar checks on the water-levels in wells around the periphery of the heavily pumped area show net declines ranging from about 7 to 10 feet during the same period.

As shown in Figure 1, the water-level in Well 1 was affected during the last part of 1940 by pumping from a new well situated nearby. It is not possible, therefore, to include this part

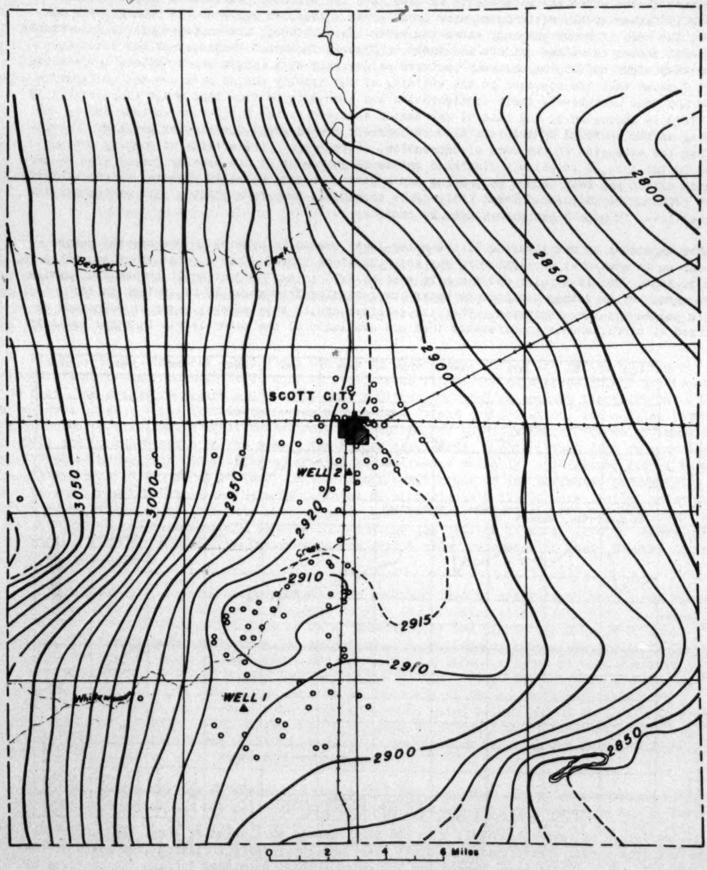

2800
2850
Beaver Creek
2900
SCOTT CITY
WELL 2
3050
3000
2950
2920
Creek
2910
2915
2910
WELL 1
Whitewoman
2900
2850
0 2 4 6 Miles

Fig. 2--Map showing contours of water-table and location of irrigation-wells, Scott County, Kansas that are included in these fault-blocks have a gentle eastward dip that is primarily the result of tilting accompanying the faulting. The structure of Parowan Valley particularly is similar to that of the plateau farther east, and the strata bordering the Valley on all sides have a comparable gentle eastward inclination; the structural units in the vicinity of the Valley are exceptional chiefly because their elevation is far below the units of the plateau, and the lowest segments, under the floor of the Valley, have been the scene of extensive deposition. The structure of Cedar City Valley is more transitional. It is bordered on the east by the Kolob Plateau block, in which the rocks are intensely folded locally along the west border, and on the west by a low range that appears to have been formed at least in part by the basin-and-range type of block-faulting.

Faults constitute the dominant structural features throughout the eastern part of Iron County. They are common throughout the area, and have displacements ranging from a few feet to several thousand feet. The major physiographic features of the region have been produced chiefly by displacements along the larger faults, and even the minor faults find common topographic expression in escarpments or in the alinement of stream-courses. Most of the faults observed appear to be high-angle normal faults, and the trace is generally fairly straight.

Hurricane Fault-Zone--The master displacement that separates the high plateaus of Utah from the Great Basin farther west is one of the most striking geologic features in the western United States, and was noted by the earliest geologists who visited the region. In 1903 Huntington and Goldthwait [see 1 of "References" at end of paper] described some of the structural and physiographic details along this displacement, which they named the Hurricane Fault, in the region beyond the south limit of the area covered in this paper. Recently Gardner has completed the detailed geologic mapping of the St. George Basin in Washington County, Utah, including the area visited by Huntington and Goldthwait, and has prepared a short preliminary report concerning the Hurricane Fault in that area [2]. He finds that the Hurricane Fault in Washington County is not a simple, continuous fracture but that it comprises a zone of displacement that may be as much as five miles wide.

In Iron County the displacements that have raised the plateaus high above the Great Basin occupy a zone that is several miles wide at the southern limit of the area near Kanarraville and that increases in width to the northward. This zone, spoken of here as the "Hurricane Fault-Zone," embraces several structural units separated by major normal faults trending northward to northeastward.

Parowan Valley lies entirely within the Hurricane Fault-Zone, and constitutes a down-faulted block, or graben, bordered on the east by the Markagunt Plateau and on the west by the Red Hills horst. Cedar City Valley has a somewhat more complex structure, comprising two narrow depressed blocks and an intervening uplifted block two to 2-1/2 miles wide that forms the ridge west and southwest of Cedar City and that is covered by the Coal Creek alluvial fan north of that town. The fault along the western edge of this raised block is considered to mark the west boundary of the Hurricane Fault-Zone. The zone includes many faults in addition to those that bound the larger structural units, because these units have been broken into smaller blocks by minor faults having displacements ranging from a few feet to several hundred feet. Displacement in the Hurricane Fault-Zone is believed to have been initiated during the Tertiary period, but the most striking structural and topographic features of the region have been produced by faulting during the Quaternary period. Displacement occurred during the Quaternary along a large proportion of the major faults, including several where Tertiary displacement was also inferred.

Evidences of faulting of the alluvial sediments--The latest movements in the Hurricane Fault-Zone have been so recent that faults can be readily identified in the upland areas that border Cedar City and Parowan valleys, because the escarpments produced by the faulting are still prominent and readily recognizable. In the unconsolidated materials of the Valley, however, the delineation of faults is more difficult, partly because the sediments are unconsolidated and unlikely to develop as pronounced an escarpment as might be formed in more rigid material, partly because deposition in the Valley is rapid enough to obliterate the effects of faulting in a short time. Many of the faults that were mapped in the upland areas could be followed only to the edge of the alluvial materials. On the other hand, several of the faults that were first identified beyond the borders of the valley-fill could be followed through the alluvium with considerable assurance, based on evidence that might be classified as physiographic, stratigraphic, or hydrologic. Some of the faults so traced were of rather large displacement--of which the westernmost fault of the Hurricane Fault-Zone is an example--but others are believed to represent only a few feet of displacement.

Physiographic evidences of faulting in the unconsolidated sediments are to be found particularly in the western part of Parowan Valley, where the rate of accumulation of detritus has doubtless been much slower than along the east side of the Valley. One fault has produced a scarp about 40 feet high west of Little Salt Lake. Farther northeast another fault has produced a scarp about 25 feet high, which can be traced for several miles. Both escarpments are clearly shown in aerial photographs.

Stratigraphic evidence of faulting of the alluvial sediments is to be found in Cedar City Valley along the westernmost displacement of the Hurricane Fault-Zone, named the Stockyards Fault. This fault borders an upland area west and south of Cedar City, but farther north its trace crosses the alluvial fan of Coal Creek, which enters the Valley at the town of Cedar City. The great majority of irrigation-wells in Cedar City Valley are located upon the Coal Creek alluvial fan, and the characteristics of the alluvial deposits are shown in a considerable number of well-logs. Practically all logs show a similar sequence of finer sediments immediately beneath the surface and a zone of coarser material below. Above the limit of the area, where wells have been drilled, coarse gravel and boulders lie at or close to the surface and it is evident that the head of the fan is and has been the site of deposition of the coarsest detritus that has been brought down the canyon. The finer sediments that underlie the surface of the lower part of the fan--including the area where wells are pumped for irrigation--are contemporaneous with the upper part of these gravels and were likely deposited under conditions existing today. The zone of coarse material that underlies these finer sediments throughout most of the pumping district is indicative that deposition of coarse detritus extended farther down the slopes of the fan in the past, when Coal Creek had greater carrying power. Because larger streams with great carrying power were generally characteristic of the glacial stages of the Pleistocene, which elsewhere in Utah culminated in Lake Bonneville, it is inferred that these coarse sediments may be correlated with Lake Bonneville sediments.

Wells on the western part of the Coal Creek alluvial fan have not penetrated thick gravel-deposits at depths comparable to the gravel in wells farther east on the fan. Coarse detritus has reached the area in the past, however, as shown by considerable amounts of gravel encountered in wells drilled to depths of more than 300 feet. The thickness of these coarse materials is comparable to that encountered in wells farther east, but the depth below the land-surface is ordinarily 200 to 250 feet greater. This difference in depth is attributed to displacement along the Stockyards Fault subsequent to the [Pleistocene] deposition of the gravels. Well-logs thus form a means of locating the trace of this fault through the unconsolidated sediments.

Hydrologic evidences of faulting of the unconsolidated sediments are clearly shown both in Cedar City Valley and Parowan Valley. The faults so indicated are not necessarily of large displacement. Instead, they may be relatively minor breaks, with displacements only sufficient to interrupt the movement of water through one or more of the alluvial aquifers. In both valleys the impeding of ground-water circulation has given rise to numerous springs, which are alined along the traces of several of the faults and which thus aid materially in mapping them.

The effect of faulting upon the movement of ground-water through the unconsolidated sediments is most clearly shown by contours of the water-table or other piezometric surfaces in both valleys. These contours show distinct ground-water dams in each valley. The dams are most clearly defined in areas where large numbers of wells are available for control in mapping. The outstanding instances of such ground-water barriers are to be found along the Stockyards Fault already mentioned, which cuts through the most intensively developed area in Cedar City Valley, and along the Culver Fault which transects the pumping district in Parowan Valley.

The ground-water dam along the Stockyards Fault is indicated by considerable differences of static level in wells of comparable depths only a few hundred yards apart. The dam follows closely the trace of the fault suggested by studies of well-logs and by projection of the fault-line recognized in geologic mapping farther south.

The ground-water dam along the Culver Fault in Parowan Valley is a very prominent hydrologic feature. For a distance of more than two miles along the Fault the piezometric surface in March, 1940, was more than 40 feet lower on the west side of the dam than on the east side. At that time there was considerable discharge from flowing wells and springs east of the ground-water dam, but water-levels in wells to the west were generally five to 15 feet below the land-surface.

Economic effects of faulting of the alluvium--Faulting has strongly influenced the economics of ground-water development both in Cedar City Valley and in Parowan Valley. This influence is most evident along the faults that traverse the areas of greatest present development, particularly the Stockyards Fault in Cedar City Valley and the Culver Fault in Parowan Valley, but it is likely that the effects of faulting would appear in other areas in the event of increased development and use of wells in those areas. The following brief discussion is limited to the economic effects of the Stockyards and Culver faults.

As a result of recent displacement along the Stockyards Fault, the thick strata of coarse detritus that ordinarily are encountered within 100 feet of the land-surface east of the Fault have been dropped more than 200 feet on the west side of the Fault and subsequently buried under a great amount of fine materials. Hence to the west of the Fault considerably deeper wells are required to reach the aquifers. These aquifers have been cut off to the east--that is, in the direction of recharge--by the faulting, and hence water removed from them is replenished more slowly than is the case in wells east of the Fault. Wells on opposite sides of the Stockyards Fault on the upper part of the Coal Creek fan reflect very clearly the contrast in water-bearing properties of the aquifers. Wells east of the Fault commonly yield more than 40 gallons a minute per foot of drawdown, whereas the yield is ordinarily less than 15 gallons per foot of drawdown in wells west of the Fault. The economic advantage of the east side of the Fault is also suggested by the distribution of irrigation-wells on the Coal Creek fan, where 39 irrigation-wells were in operation during 1940 east of the Fault and only eight were pumped on the west side, and of the unsuccessful wells drilled for irrigation, 18 are located west of the Stockyards Fault and only five east of the Fault. Some wells west of the Fault do not yield enough water for satisfactory operation of a windmill.

During the drilling of two of the deepest wells west of the Stockyards Fault the water in deeper aquifers was found to have a lower pressure-head than that in shallower strata, in contrast to conditions generally found in the unconsolidated deposits in ground-water areas in Utah. One of these wells is now pumped for irrigation, and the differential head between it and adjacent shallow wells is greater at the close of the pumping season than at the beginning, indicating that the subnormal pressure is augmented by withdrawal of water from the deep aquifers tapped by the well. Recharge to these deep aquifers has evidently been impeded by the faulting which has cut off the original source of supply toward the apex of the alluvial fan. The present differential head between deep and shallow aquifers indicates that water may be moving downward into these deep gravels.

Displacement along the Culver Fault has been so recent that a scarp about 40 feet high marks its position in the northern part of Parowan Valley. If the height of this scarp measures the extent of displacement in the central part of the Valley, the latest movement along the Fault has been considerably less than along the Stockyards Fault in Cedar City Valley. It has also been in the opposite direction, for the upthrown side of the Culver Fault is to the west. Logs of wells indicate that the aquifers on opposite sides of the Fault are generally similar in texture. As might be expected in similar types of material, wells drilled on opposite sides of the Fault are more or less similar in their yields per foot of drawdown.

The chief economic effect of the ground-water dam along the Culver Fault is the increase in depth to water and in pumping lift in wells west of the Fault. At the beginning of the pumping season there is commonly a difference of more than 40 feet in water-levels in wells on opposite sides of the Fault. During the pumping season the difference becomes greater, and by September the ground-water dam may be more than 60 feet high. The increasing height of the pondage produced by the dam during the pumping season is especially remarkable because the major development for irrigation is east of the Fault. Of 29 irrigation-wells on the Parowan Creek fan pumped in 1940, 24 are east of the Culver Fault, and 14 of these are within half a mile east of the Fault. Pumping from the five wells west of the Fault caused a disproportionate lowering of water-levels, because replenishment from the east is impeded by the barrier along the Culver Fault. The slow rate of replenishment is not limited to the pumping season, but continues throughout the year, and recovery is generally incomplete when the following irrigation-season begins. The economic effect of this lowering is indicated in the distribution of wells on the two sides of the Fault, and by the fact that five wells drilled for irrigation west of the Fault have since been abandoned.

References

[1] Ellsworth Huntington and J. W. Goldthwait, The Hurricane Fault in southwestern Utah, J. Geol., v. 11, pp. 46-63, 1903; The Hurricane Fault in the Toquerville District, Utah, Harvard Coll. Mus. Comp. Zool., Bull. 42, pp. 199-259, 1904.

[2] L. S. Gardner, The Hurricane Fault in southwestern Utah and northwestern Arizona, Amer. J. Sci., v. 239, pp. 241-260, 1941.

U. S. Geological Survey,
Salt Lake City, Utah

DEPTH OF ACTIVE SOLUTION BY GROUND-WATERS IN THE PECOS VALLEY, NEW MEXICO

Arthur M. Morgan

The Pecos River Drainage-Basin is underlain by a thick series of Permian rocks consisting largely of limestone, gypsum (or anhydrite), and halite. The beds have a regional eastward or

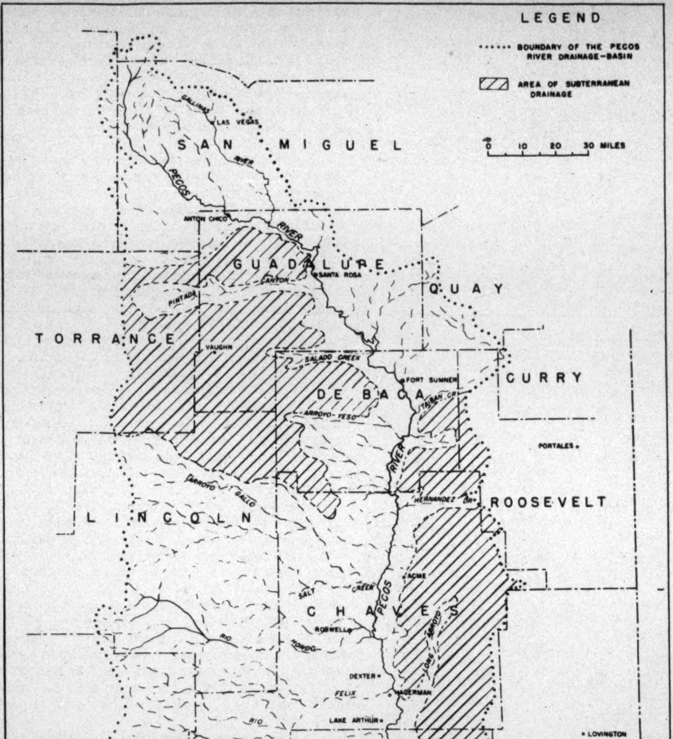

LEGEND
······ BOUNDARY OF THE PECOS RIVER DRAINAGE-BASIN
▨ AREA OF SUBTERRANEAN DRAINAGE
0 10 20 30 MILES
SAN MIGUEL
GALLINAS
LAS VEGAS
RIVER
PECOS
ANTON CHICO
RIVER
GUADALUPE
SANTA ROSA
CANTON
PINTADA
QUAY
TORRANCE
VAUGHN
SALADO CREEK
FORT SUMNER
CURRY
DE BACA
TAIBAN CR
ARROYO YESO
PORTALES
RIVER
ARROYO
GALLO
HERNANDEZ DR
ROOSEVELT
LINCOLN
ACME
SALT
CREEK
PECOS
CHAVES
ARROYO
RIO
ROSWELL
HONDO
LONG
DEXTER
FELIX
HAGERMAN
RIO
LAKE ARTHUR
LOVINGTON
MAYHILL
RIO
ARTESIA
MALJAMAR
LEA
HOPE
PENASCO
DAYTON
HOBBS
LAKEWOOD
EDDY
POTASH
MINES
OTERO
ROCKY
ARROYO
CARLSBAD
CARLSBAD CAVERNS
BLACK
RIVER
MALAGA
JAL

Fig. 1--Pecos River Drainage-Basin in New Mexico

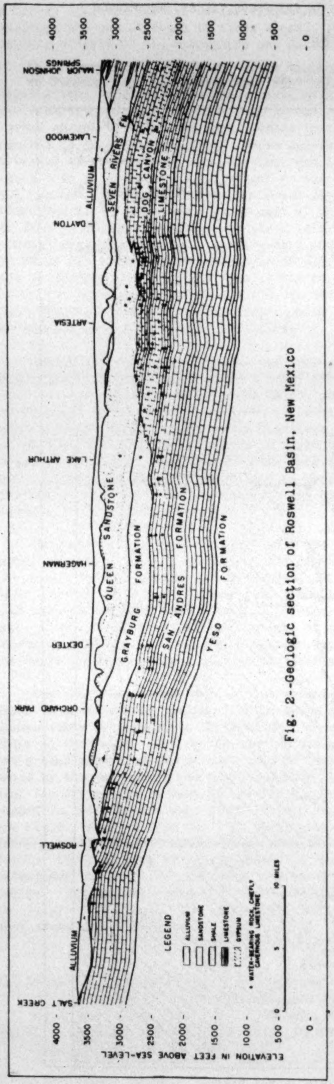

ELEVATION IN FEET ABOVE SEA-LEVEL
4000
3500
3000
2500
2000
1500
1000
500
0
SALT CREEK
ROSWELL
ORCHARD PARK
DEXTER
HAGERMAN
LAKE ARTHUR
ARTESIA
DAYTON
LAKEWOOD
MAJOR JOHNSON SPRINGS
ALLUVIUM
SEVEN RIVERS FM
DOG CANYON LIMESTONE
QUEEN SANDSTONE
GRAYBURG FORMATION
SAN ANDRES FORMATION
YESO FORMATION
LEGEND
ALLUVIUM
SANDSTONE
SHALE
LIMESTONE
GYPSUM
WATER-BEARING ROCK, CHIEFLY CAVERNOUS LIMESTONE
0
5
10 MILES

Fig. 2--Geologic section of Roswell Basin, New Mexico

southeastward dip of 40 to 80 feet to the mile and successively younger beds are exposed at the surface from west to east across the Basin (Fig. 1). The beds of the San Andres formation and the Chalk Bluff formation or its equivalents crop out over most of the broad western part of the Basin (Fig. 1). Most of the eastern part of the Basin is immediately underlain by the redbeds and sandstone of the Dockum group, of Triassic age, which, south of Acme, are separated from the Chalk Bluff formation by the Salado and Rustler formations. North of Acme the Dockum group overlaps successively older formations and northwest of Santa Rosa it rests upon beds in the lower part of the San Andres formation.

Evidences of solution of the rocks underlying the Pecos Basin are found in nearly all parts of the Basin south of Anton Chico. Sink-holes are common throughout most of the area and slumped and distorted surficial rocks testify to the activity of solution in areas where stream-erosion and deposition has obliterated or smoothed over the topographic evidences of solution and collapse. Subterranean drainage is important in most of the Basin and large areas are drained entirely underground (Fig. 1). Cavernous limestone and gypsum has been encountered in many wells at considerable depth below the surface, particularly in the Roswell Basin where cavernous zones in the San Andres and Dog Canyon limestones form the important artesian aquifer. Many workers in the Pecos Basin have pointed out local features associated with solution-phenomena in various parts of the Basin and Lee [see 1 of "References" at end of paper] described in detail the effects of solution and collapse on the development of the Pecos Basin. Nye [2, pp. 83, 180-188] also described and interpreted many of the solution-phenomena in the Roswell Basin. The formations with which solution has been associated are primarily the San Andres formation and the Chalk Bluff formation (Whitehorse group) and its equivalents in the area west of the Pecos River and the Rustler and Salado formations in the area east of the River south of the latitude of Roswell. The present paper deals particularly with solution-phenomena associated with the San Andres and Chalk Bluff formations in the area west of the River.

The San Andres formation is 1,000 to 1,200 feet thick and, in the Sacramento Mountains and the Roswell Basin, is composed of limestone with some interbedded anhydritic limestone. North of the Roswell Basin it grades into gypsum and gypsiferous limestone. Its outcrop-belt on the eastern slope of the Sacramento Mountains and in the broad upland extending from the Capitan Mountains north to Glorietta Mesa is 25 to 60 miles wide. The San Andres passes under younger beds 12 to 30 miles west of the Pecos River and underlies the River at depths of a few hundred feet to about 1,300 feet.

The Chalk Bluff formation which overlies the San Andres is about 1,700 feet thick. It consists of gypsum or anhydrite, sandstone, and red-beds in and east of the north end of the Roswell Basin but grades into limestone to the south. The Chalk Bluff is the equivalent of the Whitehorse group in subsurface farther east which has been divided into the Grayburg formation, the Queen sandstone, the Seven Rivers formation, the Yates sandstone, and the Tansill formation [3]. To the south the Chalk Bluff and its equivalents grade into limestone and in the southern part of the Roswell Basin the Grayburg formation and most of the Queen sandstone are represented in the Dog Canyon limestone. Farther south the upper part of the Chalk Bluff grades into the Carlsbad limestone. The Dog Canyon limestone thickens from a feather-edge to about 500 feet between Lake Arthur and Artesia (see Fig. 2). In the transition-zone the Dog Canyon is gypsiferous and contains innumerable small inclusions of gypsum irregularly distributed throughout much of the limestone as well as occasional thin interbedded lenses of gypsum.

In his report on the Roswell Basin, Nye [2, pp. 44-70] separated the beds described above into the "Picacho limestone" and the "Pecos formation." The "Picacho limestone" is essentially the equivalent of the San Andres formation but it includes the Dog Canyon limestone in the southern part of the Roswell Basin. The "Pecos formation" is essentially the equivalent of the Chalk Bluff formation.

The important artesian aquifer in the Roswell Basin is formed by cavernous zones in the upper part of the thick mass of limestone which Nye called the "Picacho." The cavernous zones appear to be interconnected and they form a single continuous aquifer although the aquifer rises stratigraphically as the gypsum and red-beds in the lower part of the Chalk Bluff formation grade southward into limestone. Figure 2 shows the gradation of gypsum and red-beds to limestone and the occurrence of cavernous water-bearing zones (represented by black dots). The aquifer is limited to the San Andres limestone in the northern part of the Basin. Few of the wells south of Lake Arthur penetrate below the top of the San Andres, as most of the wells bottom in the Dog Canyon limestone, but the little data available indicate that the cavernous condition of the upper part of the formation persists into the south end of the Basin. The wells in the vicinity of Artesia and Dayton that penetrated into the San Andres encountered water in the upper part of the formation. The water, however, was salty.

The artesian aquifer receives recharge principally from rainfall and seepage from the streams in the eastern part of the broad outcrop-belt of the San Andres formation on the long eastern slope of the Sacramento Mountains and in the upland-area extending north from the Capitan Mountains through Vaughn. Only a thin tongue of the Dog Canyon limestone crops out west of the southern part of the Roswell Basin but the full thickness of the limestone is exposed in the Guadalupe Mountains to the southwest. Probably some water is contributed directly to the Dog Canyon limestone in its outcrop in the Guadalupe Mountains but for the most part the Dog Canyon, in the artesian area, appears to derive its water from the San Andres.

In the outcrop-area of the San Andres formation the water-table is 200 to over 1,000 feet below the surface and in much of the area it is well below the base of the formation. In the eastern part of the outcrop-belt, 30 to 40 miles west of the Pecos River the water-table intersects the base of the formation and slopes eastward toward the river. The slope of the water-table is less than the dip of the beds and it diagonally crosses the bedding and intersects the top of the formation 12 to 15 miles west of the river. East of the point where the water-table intersects the top of the formation the water is under artesian pressure and is confined to the limestone by the less permeable red-beds, sandstone, and gypsum in the lower part of the Chalk Bluff formation.

The cavernous condition of the San Andres limestone, in its outcrop-area, extends to the base of the formation, in some places through a thickness of about 1,000 feet of beds. Throughout much of this area the cavernous zones in the limestone are far above the present water-table and, in the present cycle, the limestone in this area is exposed to solution only by downward-percolating vadose water. In earlier cycles in the history of the Pecos Basin, however, the discharge-area of the limestone aquifer occurred at much higher elevations than at present and the water-table in the outcrop-area also must have been much higher. It is impossible to determine at present how much of the solution of the limestone in the outcrop-area took place above the water-table and how much took place below. The depth to which the cavernous condition extends in some parts of the outcrop-area exceeds 1,000 feet. In the artesian area the cavernous zones in the San Andres are most numerous in the upper 300 feet of the formation although a number of wells encountered cavernous water-bearing rock at depths of about 550 feet below the top of the formation. Due to the southward component in the regional dip the depth to the top of the San Andres increases from about 150 feet at Roswell to 950 feet at Lake Arthur, 1,200 feet at Artesia, and 1,300 feet at Lakewood. The maximum depth at which cavernous zones in the San

Andres limestone were encountered by wells in the Roswell Basin is about 1,700 feet in a well near Lake McMillan.

In the southern part of the Roswell Basin where the Dog Canyon limestone forms the principal producing artesian aquifer the cavernous zones also appear to be more numerous and more persistent in the upper part of the limestone. Although cavernous limestone was encountered in the upper part of the San Andres formation in the vicinity of Artesia and Dayton the water contained therein was reported to be salty and unfit for use. The presence of salty water in the San Andres where it is overlain by 400 feet or more of cavernous Dog Canyon limestone containing fresh water suggests that active circulation of water through the artesian aquifer is essentially confined to the upper part of the aquifer and that the lower beds, although cavernous, have not yet been flushed out.

Nye [2, pp. 84-88] distinguished an unconformity at the top of the "Picacho limestone" and he suggested that the development of cavernous zones in the limestone was started in Permian time when the "Picacho" was raised above sea-level and exposed to erosion prior to the deposition of the "Pecos formation" (Chalk Bluff formation). The existence of an unconformity at the top of the "Picacho limestone," where it is the equivalent of the San Andres formation, as in the northern part of the Roswell Basin, is confirmed by petroleum geologists who have distinguished a wide-spread unconformity at the top of the San Andres [3, p. 47]. Additional data derived from recent oil-tests have shown that the "Picacho limestone" rises through about 500 feet of beds in the southern part of the Roswell Basin to include the Dog Canyon limestone as well as the San Andres and that the unconformity underlies the Dog Canyon equivalent of the "Picacho." The upper contact of the Dog Canyon limestone is gradational and has never been exposed to surface-erosion. Nye's suggestion that the development of the cavernous zones in the "Picacho limestone" was begun in the Permian therefore may apply to the San Andres but not to the Dog Canyon.

The hypothesis of intra-Permian solution affords an explanation of the occurrence of cavernous zones in the San Andres formation many miles down dip from the recharge-area at depths of several hundred feet to over 1,500 feet below the regional water-table. The occurrence of cavernous zones in the upper part of the San Andres formation which contain salt water in the southern part of the Roswell Basin supports the hypothesis in that it indicates that there has been little or no circulation of fresh water through these zones since the inception of the Pecos River. The Pecos River has cut deeper into the beds overlying the San Andres in the present cycle than at any time in the past and has afforded a better opportunity for escape of water from the San Andres and therefore a better opportunity for flushing out water trapped in the formation than at any time since the deposition of the overlying Chalk Bluff and related formations. As the cavernous zones in the San Andres in the southern part of the Roswell Basin could not have been developed by solution by the highly mineralized water contained therein at present it appears probable that the cavernous condition of the limestone was developed as Nye suggested during an erosion-interval preceding the deposition of the Chalk Bluff. The depths at which the cavernous zones in the San Andres are encountered at present are not therefore the depths at which they were developed.

On the other hand, the Dog Canyon limestone was never exposed to intra-Permian erosion and the cavernous portion of the limestone in the southern part of the Roswell Basin is probably as near to the surface at present as it has been at any time since the end of Chalk Bluff deposition. The development of the cavernous zones in the limestone must have taken place at depths as great or greater than those at which they are encountered in wells at the present time, that is, 700 to 1,200 feet beneath the surface and approximately the same depth beneath the regional water-table. The water contained in the cavernous zones of the Dog Canyon limestone appears to have been derived principally by forced upward percolation of artesian water from the underlying San Andres formation, which prior to the drilling of numerous artesian wells had head sufficient to raise the water several hundred feet above the level of the Pecos River. The water available for solution of cavities in the Dog Canyon must therefore have been already saturated or nearly saturated with calcium carbonate, having been in intimate contact with limestone through many miles of slow movement through the San Andres. However, the movement of such water through the gypsiferous limestones of the Dog Canyon could develop the cavernous condition of the formation by dissolving out the included gypsum without requiring either the time or the carbonic acid-bearing water necessary to develop the same condition in pure limestone.

The highly specialized set of conditions necessary to permit the solution of cavities in the Dog Canyon limestone by water percolating upward from the San Andres all obtain in the Roswell Basin. The conduit for the introduction of water into the Dog Canyon is supplied by the cavernous zones in the San Andres which receive recharge in the broad outcrop-area in the uplands on the flanks of the Sacramento Mountains. The beds which confine the water to the conduit and permit the development of high artesian pressure in the aquifer are the low permeable but not impermeable beds in the lower part of the Chalk Bluff formation. The discharge of water from the artesian system that permits circulation of ground-water through the Dog Canyon limestone is provided by the forced upward percolation of water through the limestone and the overlying beds of the Chalk Bluff to the surface. And finally, the gypsum in the gypsiferous limestone of the Dog Canyon in the transition-zone between the normal marine (limestone) and evaporite (gypsum and red-bed) facies of the sequence of beds is soluble in water that, being saturated with calcium carbonate, would not attack pure limestone. It is believed, therefore, that the cavernous zones in the Dog Canyon limestone were developed by solution accomplished by artesian circulation of ground-water through the gypsiferous limestone of the formation at depths up to 1,200 feet or more beneath the regional water-table.

References

[1] W. T. Lee, Erosion by solution and fill, U. S. Geol. Surv. Bull. 760, pp. 107-121, 1925.
[2] A. G. Fiedler and S. S. Nye, Geology and ground-water resources of the Roswell artesian basin, U. S. Geol. Surv. W.-S. Paper 639, 1932.
[3] R. I. Dickey, Geologic section from Fisher County through Andrews County, Texas, to Eddy County, New Mexico, Bull. Amer. Assoc. Petrol. Geol., v. 24, pp. 44-49, 1940.

U. S. Geological Survey,
Carlsbad, New Mexico

DISCUSSION

A. C. SWINNERTON (Antioch College, Yellow Springs, Ohio)--In discussing Mr. Morgan's paper I wish to review the threefold aspect which the solution-phenomena in the Pecos Valley present as a result of the underlying hydrologic and stratigraphic conditions. (1) There are large areas showing surficial effects of solution. In addition to those shown in Figure 1 where the subterranean drainage is complete, there is also the east flank of the Sacramento Mountains where the artesian aquifer has its recharge-area. (2) The permeable San Andres formation serves as an artesian aquifer because of its cavernous condition. (3) The gypsiferous Dog Canyon facies of the Chalk Bluff formation is cavernous because of vertical losses from the aquifer.

My competence to discuss this paper depends in the main on a week's visit to the Roswell Basin some years ago. The plausibility of the main point which Mr. Morgan makes in connection with upward seepage and solution in the Dog Canyon finds support in my recollection of the series of lakes and ponds just east of Roswell called the Bottomless Lakes. These ponds appear to be fed by the upward seepage of ground-water from the San Andres formation as a result of the solution and collapse of the overlying rock-material. The level of the ponds is approximately that of the piezometric surface. In addition, earlier studies by Morgan [New Mex. State Eng. Bull. 5, 1938] show that the shallow-water resources of the Roswell Basin are enhanced by seepage from the underlying aquifer.

From the physiographic point of view there are two problems which are touched on by Mr. Morgan's paper on which I trust further work is in progress. One is the extent to which the Pecos Valley has been developed by solutional slumping. The second is the extent to which the cavernous condition of the San Andres formation is inherited from an intra-Permian erosional epoch.

NOTES ON THE ELASTICITY OF THE LLOYD SAND ON LONG ISLAND, NEW YORK

C. E. Jacob
(Presented by title)

(Published with the approval of the Director, U. S. Geological Survey)

The Lloyd sand is a productive artesian aquifer underlying all of Long Island except the westernmost part. It rests unconformably upon a floor of crystalline rock that slopes toward the southeast at about 100 feet to the mile. Locally the bed-rock surface has a relief of more than 100 feet. The Lloyd sand consists of white quartz-sand and gravel, with some layers of clay. It is considered to be part of the Raritan--the basal formation of the Upper Cretaceous series. At Rockaway Park, on the south shore of the Island, the Lloyd is about 200 feet thick and is overlain by 300 feet of clays of Raritan age. The Raritan clays are in turn overlain by about 150 feet of sands, believed to be of Magothy age, and about 315 feet of Pleistocene sediments.

Table 1--Pertinent data regarding pumping test of wells ending in the Lloyd sand at Rockaway Park, Long Island, New York, January and February, 1940

Period test	Change of discharge (beginning of period), gpm	Time of occurrence of change in discharge	Well in which change occurred
		h m 1940	
1	+2,210	9 45, Jan. 29	Q 1071
2	-2,210	15 30, Feb. 2	Q 1071
3	+1,770	10 12, Feb. 5	Q 1071
	+1,790	10 21, Feb. 5	Q 1030
4	-1,770	14 15, Feb. 14	Q 1071
	-1,790	14 15, Feb. 14	Q 1030
5	+2,130	10 40, Feb. 19	Q 1030
6	-2,130	15 30, Feb. 23	Q 1030

In a previous paper by the writer [see 1 of "References" at end of paper] there were given the results of a preliminary pumping test of Well Q-1030, at Rockaway Park, which was conducted from May 18 to 22, 1939, when the well was under construction. This well and a second well nearby, both owned by the City of New York, have since been completed. Well Q-1030 (known to the owner as No. 2) was finished in the Lloyd sand with 65 feet of 12-inch screen between 720 and 785 feet below sea-level. The second one, Well Q-1071 (owner's No. 1), is about 420 feet to the northeast of Well Q-1030. It was also finished with 65 feet of 12-inch screen, between 760 and 825 feet below sea-level. (The general land-surface is about eight feet above sea-level at both well-sites.) Both of these wells were under-reamed to 36 inches and were gravel-packed.

Beginning at 9:45 a.m., January 29, 1940, Well Q-1071 was pumped for four days at 2,210 gpm (see Table 1). After a three-day recovery-period, wells Q-1071 and Q-1030 were pumped together at a combined rate of 3,560 gpm. This pumping period lasted nine days and was followed by a recovery-period of five days. Then, beginning at 10:40 a.m., February 19, Well Q-1030 was pumped alone for four days at 2,130 gpm.

Throughout this test periodic measurements were made of the depth to water-level in wells Q-1030 and Q-1071 and automatic water-level recorders were maintained in operation on other Lloyd wells in the vicinity of Rockaway Park. In order to correct the water-levels for tidal fluctuations, a recording tide-gage was maintained on Jamaica Bay at Rockaway Park. However, because of adverse conditions of weather the operation of this gage was not continuous. The data given in this paper are for the fourth and fifth periods of the test only, during which periods the tide-gage was in continuous operation. The tidal fluctuations were reduced by comparing the water-level graphs for those periods with the tide-record by hours. It was found, however, that the accuracy of the data was in general such as not to warrant that procedure. The data are now being recomputed on the basis of "highs" and "lows" only, using the continuous tide-record at Sandy Hook as a reference. However, in order to amend the preliminary data and the conclusions tentatively drawn therefrom, it seems desirable to report now on the results that have been obtained thus far from the test in 1940.

In the paper previously referred to there were given values of transmissibility and of the coefficient of storage obtained by application of the "graphical method" to drawdowns observed during the preliminary test in four wells in the vicinity of Rockaway Park. The meager data for Well Q-288 gave a coefficient of storage of 8.0×10^{-4} and a transmissibility of 114,000 gpd/ft [1, Table 1, p. 582]. Because of the low discharge-rate of Well Q-1030 during the preliminary test (310 gpm), the drawdown in Well Q-288, approximately 4,100 feet away, was only a few tenths of a foot. As the tidal range in that well is about two feet on the average, the errors of reduction were comparatively great. For Well Q-287, approximately 10,200 feet from Well Q-1030, the errors were even greater proportionately, so that it was not possible to make a separate determination of values of S and T from the data for that well. However, by combining the data for these two wells and applying the graphical method, it was later found that $S = 3.0 \times 10^{-4}$ and T = 190,000 gpd/ft, as given in Table 2. It is seen that these figures compare favorably with the corresponding results from the pumping test of 1940. The latter are based on separate

Table 2--Summary of results of pumping tests of the Lloyd sand near Rockaway Park, Long Island, New York

Date test	Observation-well	Distance (feet) and direction from Well Q-1030		Transmissibility T, gpd/ft	Coefficient storage S
May, 1939	Q-288 Q-287	4,100 10,200	E-NE N-NE	190,000	3.0×10^{-4}
Jan. and Feb., 1940	Q-288	4,100	E-NE	180,000	2.8×10^{-4}
	Q-287	10,200	N-NE	160,000	2.9×10^{-4}
	K-1057	13,000	W	170,000	3.0×10^{-4}

Table 3--Data on the effective compressibility of the Lloyd sand in the vicinity of Rockaway Park, Long Island, New York

Source of data	Tidal fluctuations, Well Q-288	Pumping test, Observation-Well Q-288
Tidal efficiency, C	0.42	----
Coefficient of storage, S	----	2.8×10^{-4}
Ratio of effective compressibility to compressibility of gas-free water	1.7[a]	2.8
Modulus of compression of skeleton of aquifer, E_s in lb/in^2	1,200,000	480,000
Gas-volume required to account for effective compressibility, assuming incompressible aquifer (fraction of pore-space) in per cent	----[b]	0.2

[a] $1/B = 1/(1 - C) = 1/0.58 = 1.72$. [b] Tidal fluctuations cannot be accounted for on assumption of incompressible aquifer.

graphical determinations for the recovery during the fourth period of the test and the drawdown during the fifth. Each of these values of S and T represents, therefore, the average of two figures.

Assuming a rigid aquifer confined between impermeable beds, having a porosity of 35 per cent and a thickness of 85 feet, the value of S ($= 8.0 \times 10^{-4}$) previously determined from the data of 1939 for Well Q-288 would indicate an effective fluid compressibility 18.6 times the compressibility of gas-free water. That is, $S/(\rho g \theta m/E_w) = 8.0 \times 10^{-4}/4.3 \times 10^{-5} = 18.6$. It was erroneously stated elsewhere by the writer that "the Lloyd sand, with the water that it contains, appears to be from about 3.4 to 17.6 times as compressible as water alone" [1, p. 585]. It is evident that each of these figures is too small by one. However, in view of the more recent determinations of the value of S, the latter figure would appear to be much too large. Moreover, the proper value of thickness, m, for Well Q-288 is probably about 200 feet instead of 85 feet as previously assumed. Formerly it was thought that the Lloyd sand should be considered as two distinct water-bearing beds separated by a bed of somewhat impermeable material. A thickness of 85 feet was ascribed to the upper water-bearing horizon. However, on the basis of more recent information it would appear that, at least in the vicinity of Rockaway Park, the Lloyd is to be considered a single unit, hydrologically speaking. Thus, on the basis of the present data, the ratio of the effective compressibility of the Lloyd sand to the compressibility of gas-free water is $S/(\rho g \theta m/E_w) = 2.8 \times 10^{-4}/(0.35 \times 200/6.9 \times 10^5) = 2.8$, as given in Table 3. Here the porosity, θ, is again taken as 0.35, and the bulk modulus of water is expressed in terms of equivalent head as $(E_w/\rho g) = 6.9 \times 10^5$ feet.

The values of the modulus of compression of the skeleton of the aquifer given in Table 3 were computed from equation (10) given in the earlier paper by the writer [1]. These values are excessive compared to experimental values usually given for unconsolidated sediments. For stresses ranging from zero up to the probable maximum, for the Lloyd sand at Rockaway Park, moduli of elasticity determined experimentally are generally of the order of 10^3 or 10^4 lb/in^2. In attempting to reconcile these two sets of data, differences in conditions of loading should be recognized. In the laboratory, elastic constants are determined by subjecting the (recomposed) material to a continuously and gradually increasing load. The familiar compression-test diagram obtained in this way shows the porosity to be a single-valued function of the stress. Values of the elastic modulus computed therefrom increase uniformly with the stress. However, if during a compression-test of this kind the load is gradually relaxed, a lower, "descending" branch of the curve is obtained, giving a still higher value of modulus. Subsequent reloading will produce a second "ascending" branch of the curve, and so on. The value of elastic modulus from a descending branch of the curve is generally several times that from the preceding ascending branch, the ratio between the two generally increasing with the stress.

By the same token, a load fluctuating within narrow limits will produce a series of short ascending and descending branches of the stress-strain curve which continuously approach coincidence. And, however complex the stress-strain history of the material may be, after a sufficient number of such fluctuations an abnormal elastic condition may be established, under which the ascending and descending branches of the curve do coincide. In such a case, the apparent value of the elastic modulus may be exceedingly large as compared to the experimental value determined over the same range of stress. This would seem to be a logical explanation for the high apparent value of the modulus of compression of the skeleton of the aquifer determined from the tidal fluctuations (1,200,000 lbs/in^2). The mean range of tide at Sandy Hook being about 4.6 feet, the tide superimposed upon the "dead load" of the beds overlying the Lloyd may be considered to represent a fluctuation in load of about 0.2 per cent at a depth of 1,000 feet (that is, assuming the average specific gravity of the overlying beds to be 2.3). Since the last supposed eustatic change in sea-level this load has fluctuated a few million times over essentially the same narrow range, assuming the head in the Lloyd to have remained constant since that time.

The difference between the apparent modulus of compression determined from the tidal fluctuations (1,200,000 lbs/in^2) and that determined from the pumping test (480,000 lbs/in^2) may likewise be explained, partly at least, on the basis of the range of stress involved. During the pumping test of 1940 the head in the Lloyd sand declined to a new low over a considerable area in the vicinity of the pumped wells, and consequently the stress in the skeleton of the aquifer reached a new high. It is to be expected that the modulus of elasticity would be smaller for the new, higher range of stress than for the old range, over which the stress had fluctuated many times.

It should be noted that the computation of values of E_s by equation (10) [1] is based on the assumption that there is no leakage across the contact between the aquifer and the confining beds. It would seem that equation (1), from which equation (10) is derived, is strictly valid only for a steady state, although that steady state might involve leakage. However, because of the variable leakage-factor in the non-steady state, the effective compressibility of the aquifer may vary depending on the manner and rate at which the change in stress occurs. The effective compressibility may vary depending on whether the change in stress results from a change in the superimposed load or from an independent change in the internal fluid pressure. This might also be a partial explanation of the difference between the value of E_s determined from the tidal fluctuations and that determined from the pumping test.

The division between $(1 + E_w/\theta E_s)$ and (cE_w/E_c) indicated in Table 2 of the previous paper should be regarded as artificial. Here $(E_w/\theta E_s)$ and (cE_w/E_c) have been lumped together. The values of modulus of compression given in Table 3 of this paper, although designated by E_s, may be regarded in effect as representing $1/[(1/E_s) + (c\theta/E_c)]$, in which (c/E_c) is the "variable leakage-factor" referred to above.

An alternative explanation for the high apparent compressibility of the Lloyd sand is that there might be pockets of gas dispersed throughout the sand. From equations (2), (9), and (10) [1], $S = d(\rho\theta m)/\rho dh$. Assuming the skeleton of the aquifer to be incompressible, $(dm/dh) = 0$, and $(d\theta/dh) = 0$. Let (θ_w/θ) represent the fraction of pore-space occupied by water and let (θ_g/θ) represent the fraction occupied by gas. Then, $S = m[(\theta_w d\rho/\rho dh) + (d\theta_w/dh)]$. But, $(d\rho/\rho dh) = (\rho g/E_w)$; and for isothermal conditions, $(d\theta_w/dh) = -(d\theta_g/dh) = (\rho g\theta_g/p)$. Thus $S = m[(\rho g\theta_w/E_w) + (\rho g\theta_g/p)]$. For small values of θ_g, it may be assumed that $\theta_w = \theta$. Then $S = \rho g\theta m[(1/E_w) + (\theta_g/\theta p)]$.

From this the relative volume of gas required to account for the observed storage-coefficient, assuming an incompressible aquifer confined by impermeable beds, is

$$(\theta_g/\theta) = (p/E_w)[(SE_w/\rho g\theta m) - 1]$$

Expressing p and E_w in terms of equivalent head, assuming the average depth to the middle of the Lloyd to be 865 feet and adding 35 feet to include the pressure of the atmosphere, $(\theta_g/\theta) = (900/690{,}000)[2.8 - 1] = 0.0023$. In other words, in order to account for the apparent compressibility on the basis of these assumptions, about 0.2 per cent of the pore-space in the Lloyd sand would have to be occupied by gas. However, it is evident that the foregoing assumption regarding the compressibility of the aquifer is not compatible with the fact that tidal fluctuations occur in the Lloyd. An incompressible aquifer overlain by as much as 300 feet of clay would not show tidal fluctuations.

Taking into consideration all the factors that contribute to the compressibility, the coefficient of storage may be expressed as

$$S = \rho g\theta m[(1/E_w) + (b/\theta E_s) + (c/E_c) + (\theta_g/\theta p)]$$

This equation replaces equation (12) in the previous paper [1].

Although on the basis of pumping tests of a few days duration the Lloyd sand, with its contained water, appears to be only about three times as compressible as water alone, elsewhere higher apparent compressibilities have been found. For example, on the basis of two-year drawdowns observed at distances ranging from 4-1/2 to 15-1/2 miles from the center of pumping near Houston, Texas, Guyton [2] determined coefficients of storage ranging from 0.0016 to 0.0054 and averaging 0.0033. The beds in question represent a 600-foot thickness of Coastal Plain sediments ranging in age from Miocene to Recent. In this case $(\rho g \theta m/E_W) = 3 \times 10^{-4}$. In other words, the apparent compressibility is on the average about 11 times the true compressibility of water. However, as in the case of the Lloyd sand, it is not possible at present to determine just what proportion of the excess compressibility is to be ascribed to the sands, what proportion to the clays, and what proportion to any gas that might be trapped therein.

Acknowledgment--The pumping tests at Rockaway Park were made possible by the cooperation of the Department of Water Supply, Gas and Electricity of the City of New York, for which appreciation is hereby expressed.

References

[1] C. E. Jacob, On the flow of water in an elastic artesian aquifer, Trans. Amer. Geophys. Union, pp. 574-586, 1940.

[2] W. F. Guyton, Application of the coefficients of transmissibility and storage in the Houston District, Texas, Trans. Amer. Geophys. Union, 22nd Annual Meeting, 1941.

U. S. Geological Survey,
Jamaica, New York

PAPERS, SECTION OF HYDROLOGY

NATIONAL ACADEMY - RESEARCH COUNCIL BUILDING
THIRD SESSION, 9:00 A.M., MAY 2, 1941

U. S. COAST GUARD CUTTER *NORTHLAND'S* ICE AND OCEANOGRAPHIC OBSERVATION CRUISE, BAFFIN BAY AND DAVIS STRAIT, AUTUMN OF 1940

Ed. H. Smith
(Presented by title)

During the latter part of 1939 and at the April, 1940, meeting of the International Commission of Snow and Glaciers, attention was called to the desirability of taking an iceberg-census three successive summers for the value this information might have for ice-studies in general and particularly to the efficient operation of the International Ice Patrol. The subject was presented to the Interdepartmental Board on Ice Observation, Ice Patrol and Derelict Destruction Service, at its annual meeting in December, 1939. The Board recommended that a survey of the present iceberg-glacier fronts, and also the waters of Baffin Bay and Davis Strait, be carried out for three successive summers, beginning with 1940, if the Coast Guard could furnish the necessary ship for the cruise. The Commander, International Ice Patrol, recommended that the oceanographic and ice-observation cruise be carried out by two separate vessels, the *General Greene* continuing with her usual cruise to Cape Farewell, and at the proper time during the summer, the iceberg-observation cruise to Baffin Bay and Davis Strait be carried out with a Lake-type cutter. At the request of Headquarters, as Commander, International Ice Patrol, I submitted a final letter on the subject, recommending that the ice-observation cruise to Baffin Bay be performed by the Cutter *Northland*. No opportunity, however, appeared likely for the summer of 1940 until the *Northland* received orders to Greenland duty, and later, in August, when the latter was curtailed, the *Northland* became available for the earlier discussed cruise to Baffin Bay and Davis Strait, as authorized.

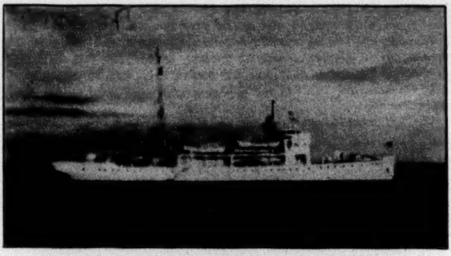


Fig. 1--U. S. Coast Guard Cutter *Northland*

We sailed from Ivigtut on September 5, proceeding to Godhavn, where we stopped for a few hours, then to Disko Bay and Vaigat to Umanak Fiord, and Karrat Fiord. Disko Bay, Umanak, and Karrat fiords are said to embrace iceberg-producing glaciers which account for almost half the supply of bergs annually calved from West Greenland glaciers. The *Northland* visited the principal glaciers of Great and Small Karajak--Rink and Umiamako glaciers. Several experienced local Danes were interviewed at various settlements in this region regarding the amount of icebergs discharged from the glaciers, and the general drift of the bergs out of the fiords. The ship then continued northward, visiting the settlements of Prøven and Upernivik. At Upernivik several persons of reputed local knowledge were interrogated regarding the discharge of the important glaciers in this region--that is, Upernivik, Gieseke, and Hayes glaciers. The course was pursued northward to the vicinity of the Duck Islands, thence across Melville Bay to Cape York, thence across the southern part of Smith Sound to Devon Island, thence southward along the mouth of Jones Sound, Lancaster Sound, past Bylot Island, and southward along the Baffin Land Coast.

Oceanographic sections A and B, of approximately 100 and 60 miles, respectively, were occupied in the final oceanographic unexplored portion of Baffin Bay. The cruise then continued southward along the Baffin Land Coast, rounding Cape Dier, thence towards Cumberland Sound,

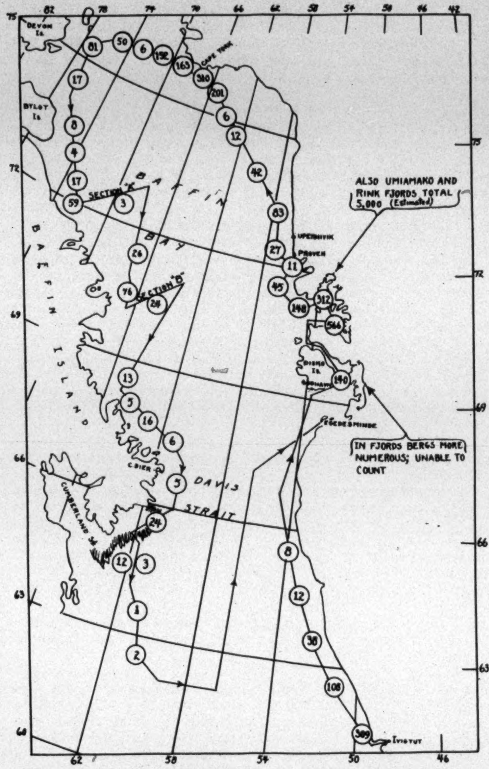

DEVON Is.
BYLOT Is.
CAPE YORK
UPERNIVIK
PROVEN
DISKO Is.
GODHAVN
EGEDESMINDE
C. DIER
CUMBERLAND Sd.
IVIGTUT
BAFFIN BAY
BAFFIN ISLAND
DAVIS STRAIT
SECTION "A"
SECTION "B"
ALSO UMIAMAKO AND RINK FJORDS TOTAL 5,000 (Estimated)
IN FJORDS BERGS MORE NUMEROUS; UNABLE TO COUNT
81
50
6
192
165
310
201
6
12
42
83
27
11
45
148
312
566
140
17
8
4
17
59
3
26
76
24
13
5
16
6
5
24
12
3
1
2
8
12
38
108
309
82
78
74
70
66
62
58
54
50
46
42
75
72
69
66
63
60

Fig. 2--Map of iceberg-distribution in Baffin Bay, Davis Strait, and West Greenland coastal waters, September 5 to 23, 1940

thence southward into the northern part of the Labrador Sea midway between Baffin Land and Greenland, where the cruise terminated on September 23.

During this period of 18 days the Northland cruised a total of 3,360 miles, and sighted a total of 3,289 icebergs. The general location of the bergs is grouped and plotted as circles showing the number of bergs sighted in that area (Fig. 2). It was found that the bergs were most numerous within a coastal zone of 15 miles, farther offshore they became quite scattered to sparse, and farther than 40 miles out they were seen only occasionally. It would appear from our observations that in the central portions of Davis Strait and Baffin Bay the number of bergs was small. Based on the above distribution and those samplings which we were able to carry out along the ship's track, it is estimated there were during this period a total of 6,000 bergs in Baffin Bay and Davis Strait. The immediate vicinity of glacier-fronts, of course, contained the most. In Umanak Fiord, in a distance of about 30 miles, a total of 566 bergs were counted. It was stated at the settlement that the Fiord contained many more bergs than this during every June when the winter's ice becomes broken up and that the bergs are released in larger numbers. It was possible to cruise the ship fairly close to the front of the Great Karajak Glacier, but impossible to do so at Rink and Umiamako glaciers. In this respect the latter two are similar to Jacobshavn in that the constricted part of the fiord several miles in length leading to the glacier-front is normally clogged with bergs, one against another. It was estimated that there was a total of 5,000 sizable bergs thus jammed in Umiamako and Rink fiords on September 10. A similar condition prevails at Jacobshavn Fiord where in 1928 I estimated the Fiord contained 6,000 bergs.

After drifting out of the fiords into Disko Bay, Umanak, and Karrat fiords, the majority of the bergs apparently are turned northward by the current and, thus joined by many more bergs from Upernivik, Giesecke, and the bergs from Melville Bay. They follow northward along the Greenland side, thence westward and eventually reach the southflowing Baffin Land Current. This is the previously regarded general drift, but not all persons interviewed during the trip agreed on some of these generally accepted views. At Upernivik several were of the opinion that the bergs there drifted southwestward across to the Labrador Current, although no person had ever traced the drift offshore. The abundance of bergs met between Disko Bay and Cape York would appear to indicate that the latter point marked approximately the progress which the crop during the season of 1940 had made since being released from their respective discharge-points. This is shown by the relative numbers plotted in Figure 2; a marked diminution in abundance noticeable as the vicinity of Cape York was left and American shores approached. The bergs themselves also had a sharper, more rugged, newer appearance east of Cape York than those observed later, along the western side of Baffin Bay and Davis Strait. The number of bergs, from all the accounts of the Greenlanders, was about normal but some glaciers this summer were claimed to be less productive than normal, while others were more prolific. This feature of a variation in the annual rate of iceberg-discharge has never been seriously considered before, but is one which may have an important bearing on the variation in the numbers of bergs observed every spring off Newfoundland.

When in the Vaigat on September 10, we measured the second highest berg of record, 406 feet above the sea. Several were measured with heights greater than 300 feet. The longest berg was met off the Baffin Land coast on September 14. It was in the form of a chain of flat-topped bergs that, shortly prior to our arrival, had been one single berg that must have totalled five miles or so in length. The largest piece, which was separated from the other smaller ones by gaps of two or three ship's lengths, measured 2.3 miles. The height which was quite uniform, was only 45 feet. Although this chain of ice-islets was more than 20 miles from the nearest land, and a heavy ocean swell prevailed, two polar bears were sighted cantering along the top of the berg (polar bears have been sighted in the open sea more than 100 miles from land), then disappeared in towards the center, apparently frightened by the sight of the ship. It is believed they had become marooned there as the ice-island had drifted farther and farther away from the shore. The known greater prevalence of bears in the region of Ellesmere Land than Greenland might indicate the former as the probable origin of this ice.

It is interesting to note that throughout our tour of Baffin Bay and Davis Strait, no pack-ice (sea-ice) was found except a rather small field in the vicinity of Cumberland Sound (see Fig. 2). September, as a rule, witnesses a minimum amount of pack-ice in Baffin Bay when the fields are usually restricted to the Baffin Land coast and offing. The condition, however, where not a single scrap of pack-ice exists in Baffin Bay, even in September, is unusual. Our observations agree with those reported by the schooner Effie M. Morrissey (Captain Bob Bartlett) which crossed Melville Bay in the latter part of July, in which the remarkable scarcity of ice and the high temperature of the surface-water were subjects of comment. The Northland found relatively abnormal warm surface-water, with temperatures recorded as high as 40° on the Greenland side and 36° off the Baffin Land Coast. When we cruised past the entrance of Lancaster Sound no ice whatever could be seen to the westward with excellent visibility, and the opinion is advanced that a ship built for ice-navigation could have easily proceeded through and into the Pacific a few weeks earlier.

During our ice-observation cruise September 5 to 23, 1940, five of the principal iceberg-glaciers which discharge a large proportion of the icebergs that drift southward towards the trans-Atlantic steamship-lanes, were visited. At nearly all settlements several of the Greenland officials were interviewed and much information was collected regarding the behavior of the glaciers and the discharge of the icebergs. It was the general opinion that there was considerable variation in the number of icebergs from year to year.

When inquiries were made regarding the approximate number of bergs from the nearby glaciers nobody appeared to have the slightest idea but they all considered it possible to count. It so happens, moreover, that at strategic points of observation along the paths of dispersal of several of the most important iceberg-glaciers, there are settlements at which designated ob-

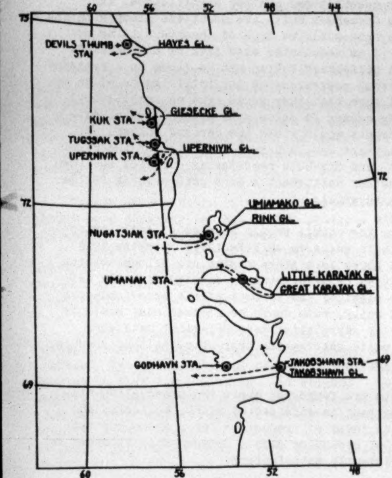


Fig. 3--Map showing proposed iceberg observation-stations

servers could, without difficulty, maintain a daily count of the icebergs drifting past. The larger settlements are under the control of a Government representative called the Kolonibestyrer, and in the smaller places a Udstedbestyrer. The Kolonibestyrers come under the direction of the Landsfoged (Governor) of Greenland (Greenland Authority).

The important glaciers from which a count of icebergs would be desirable and the settlements at which a station observer could maintain a log of passing bergs (Fig. 3) are as follows:

Glacier	Observation-station
Jacobshavn	Jacobshavn Settlement, Godhavn
Karajak	Umanak Settlement
Rink, Umiamako	Nugatsiak
Upernivik	Tugssak
Giesecke	Kuk
Hayes	Devils Thumb

This daily counting should begin on the breaking up of the fiord-ice and the release of the bergs normally in June and would cease with the freezing-in of the fiord usually in December. The service should be standardized and repeated for a test period of at least three years. The records should be assembled by the Greenland Authority at the termination of the season and forwarded to the Commandant, United States Coast Guard. Any remarks of interest regarding the dates of the iceberg-season, effects of weather, etc., would also be beneficial.

It is felt that the results of this 18-day ice-observation cruise were well worth while. Most important was information as to the approximate number and distribution of bergs which have been drifting during this summer in these northern waters and which will continue to drift southwards towards the Atlantic this winter. Thus we are furnished with a clue of the character of the iceberg-season more than six months in advance, the spring of 1941, off Newfoundland. Several other subjects of interest, such as the variation in iceberg-productivity of a glacier, which have been revealed as a result of direct observation promise to bring clearer and more intelligent views to the iceberg-problems. It is hoped that similar cruises will be undertaken by the United States Coast Guard during the summer of 1941 and 1942 in order that comparisons may be made and conclusions of value may be drawn.

U. S. Coast Guard,
Washington, D. C.

DISCUSSION

MAX DEMOREST (Yale University, New Haven, Connecticut; communicated)--First, I should like to emphasize the eminent worth of Commander Smith's proposed program and to express the hope that it will be carried through without interruption. Obviously the data gathered will be of interest and value not only to his own work as Commander of the International Ice Patrol, but also to glaciologists, oceanographers, and climatologists.

Second, in connection with the proposed observation-stations along the Greenland Coast I should like to raise some questions and offer some suggestions.

In the counting of bergs I wonder how much discrimination is exercised, for there are bergs of all sizes--giants that rise 200 to 400 feet out of the sea and babies that are mere chips to be measured in inches rather than in feet. Obviously it is only those of more than a certain size that can survive long enough to reach more southern waters. But what is that certain size? Perhaps the studies contemplated will answer as well as raise this question. However, in connection with the proposed observation-stations this question has another significance, for though experienced and interested observers such as Commander Smith are doubtless discriminating in their counts of bergs, I do not believe that the same would be true of observers to be selected for daily counts along the Greenland Coast. I am acquainted with five of the seven localities proposed and feel sure that no more than a half-breed Eskimo can be found as a resident at four of those localities. Now I do not wish to cast aspersions on the intelligence of an Eskimo--especially a half-breed Eskimo--but I do feel sure that they would take no intellectual enjoyment from their task. If we may judge from the manner in which some meteorological data are collected by Eskimos, I simply doubt that the counts would yield the desired values. At Upernivik the native meteorological observer of ten years ago, who supplied data for the Royal Danish Meteorological Institute, carefully took wet- and dry-bulb readings as directed and then averaged the two for his temperature record. At another settlement a more enterprising fellow occasionally made out his data-sheets for a week in advance!

I should also like to raise the question of why the counts should be made at daily intervals. Would not intervals of a week or even a month be quite as satisfactory? I raise this question because daily differences in the number of bergs in a given region are seldom obvious and it is only counts over longer time-periods that can be discriminated as significantly different. Were it possible to place observers within sight of the termini of the berg-producing glaciers and to count the numbers of bergs produced daily, data could be secured that would be of particular interest to glaciologists--especially if correlative meteorological data were available. Unfortunately, however, Eskimos do not build settlements near glaciers that produce numerous bergs, nor do they like to travel in berg-infested waters.

At the more distant localities where settlements are found and where the observation-stations would be located, the number of bergs drifting past is affected by winds, currents, and stranding, so that any one count would not furnish an index of production for a given day but rather an index of average production over a number of preceding days. Consequently it seems to me that weekly or even monthly counts might be sufficiently satisfactory.

Possibly this suggestion has further value since an Eskimo's reliability for such tasks as berg-counting may be expected to be inversely proportional to the number of times he has to perform the task. An Eskimo observer who would begin to substitute guesses for counts at the end of the first week of daily observations might very well go through an entire season of monthly counts without his conscience failing him.

At the risk of presenting an entirely impracticable scheme I should like to suggest that counts be made from aerial flights. An airplane taking off from Egedesminde or Godhavn and flying north to Melville Bay and returning at a fairly high altitude could take sufficient oblique photographs to show the density of bergs in the critical areas. Three or four flights made between the first of June and the first of October would yield abundant data of a thoroughly reliable nature. Unfortunately it may be that the expense of such operations would make them prohibitive.

Finally, I should like to point out another factor that may be of interest. That is the effect of temperature on the nature of iceberg-production. I rather doubt that the amount of ice discharged into the sea by the large Greenland glaciers varies significantly from year to year (though there must be appreciable variations over periods of many years). Yet there are yearly differences in the character of berg-production. Experiments now under way show that even the surface-ice of a glacier is plastic under slowly accumulating stresses and that such surface-plasticity increases very greatly as the temperature approaches the melting point. This means that warm surface-temperatures favor glacier-movement with a minimum of crevassing whereas cold surface-temperatures cause a maximum of crevassing. Thus bergs formed in a cold summer season should be more numerous but smaller and more highly fractured (and therefore subject to more rapid disintegration) than those formed in warm seasons. Consequently a cold season would furnish relatively few bergs of sufficient size and strength to survive the long and circuitous drift to more southern waters.

ICE-CRUSTS AND SNOW-SETTLING, SNOQUALMIE PASS, WINTER OF 1940-1941

Phil E. Church

During the winter of 1939-40, the changes occurring to ice-crusts and the settling of the snow at Snoqualmie Pass were followed by a series of seven observations made at approximately two-week intervals. The observations were made without a snow-sampler. Changes in density and water-content, therefore, could not be obtained. However, by spreading dyes on the top of the snow at several visits and measuring the height of these dyed layers later (by cutting a profile through the snow) certain features of the changes of a snow-cover were explained [see 1 of "References" at end of paper].

Though observations of the same type were made during the winter of 1940-41, the data obtained were superior to that of the previous winter because a snow-sampler was loaned to the University by the Weather Bureau. Again, the excellent records of weather kept at the Pass by L. C. Maybee (until March 1) and Weisner (after March 1) were available; these, too, were indispensable. The test-plot was visited six times between November 11 and March 23, the interval between each observation being about four weeks. Neither time nor money was available to make more frequent trips. However, having the snow-sampler permitted fewer inspections.

With the sampler, the usual method of vertical boring was used to determine the total water-content. After several samples were taken, a trench was shovelled out to expose the snow-profile. The distance below the surface of each important crust was then measured and vertical samples to that depth were cut and weighed. This procedure permitted the calculation of the density of each layer. At the suggestion of R. A. Work, Division of Irrigation, Soil Conservation Service, Medford, Oregon, lateral sampling between the crusts supplemented the vertical sampling on the visits in February and March. Cores from 30 to 50 inches in length were cut and weighed. This method gave a more accurate figure of the density than the vertical sampling-method.

The winter of 1940-41 was similar to the previous one in that there was less snow than average, but the former year had a much greater deficiency than the latter. November was the only month that had the average amount on the ground. The maximum for the winter was reached January 26 with 66 inches (15-year average, 77 inches on that date). The winter was singular in that there were only seven snowy storms that left more than ten inches each. Between these storms little snow fell. The general increase of depth on the ground, therefore, revolves around the major storms.

The first storm (November 7 to 10) left a cover of 18 inches and was followed immediately by cold weather (minimum 10° F). The melted content of the 25-inch fall, which formed the 18-inch cover, was 2.52 inches. The first visit was on November 11 at which time bluing was spread over the surface of the homogeneous light new snow. The coloring matter froze to the cold (10° F) snow and was covered by a fresh fall before any appreciable melting began. Settling of the first snow was rapid, but intermittently enough snow fell to keep the depth at about 15 inches until December 18.

During this relatively snowless five-week period, a second visit, on December 5, was made. Sampling showed that the bluing was in the bottom four inches and that this layer contained nearly two inches of water. The top eight inches had three inches of water. Though the temperature had fluctuated from above freezing during the day to below freezing at night, no important crusts formed. The column now had a water-content of five inches, although snow and rain from November 7 to December 5 equalled 11.14 inches. Thus the snow-cover had been unable to absorb much of the rain. Red dye was sprinkled over the surface at the conclusion of the inspection.

It was cold (minimum from 9° F to 25° F) from December 10 to 18 with neither rain nor snow. Two days of snow, after December 18, increased the depth on the ground to 27 inches at which time a second application of red dye was spread. Though the depth was only 24 inches on December 25, a steady fall during the next week brought the total on the ground to 36 inches. Since November 7, 19.58 inches of water (snow and rain) had fallen.

An inspection on January 3 showed a total of 11 inches of water in the 36 inches of snow, giving an average density of 34 per cent. The density, however, was not homogeneous from top to bottom. A definite porous crust 2.5 inches thick was present some five inches below the top of the cover. Above this the new snow had a density of 12 per cent; below, down to the top of the upper red layer (now 17 inches above the ground) the density was 27 per cent. The upper and lower red layers merged to form a single red zone some nine inches thick (8 inches to 17 inches above the ground) with a density of 40 per cent. Below that, the five-inch layer had sustained a slight decrease (seven per cent) of density. The blue snow was now only three inches thick, and had a density of 50 per cent. Bluing again was applied; it froze almost immediately, for the temperature was 20° F.

During January, three storms (4 to 8, 15 to 18, and 25 to 26) brought the depth to 66 inches on the last date. By the first of February a total of 28.58 inches of water had fallen since the beginning of the snow-season; an inspection on February 1 showed the snow-cover had a water-content of 19 inches. The depth was 58 inches, the top 12 inches being 20 per cent water. At 46 inches above the ground a porous crust half an inch thick had formed. Below that was a 20-inch layer which from horizontal sampling showed a density of 33 per cent. This layer was superincumbent on the blue-stained snow, the latter having dropped ten inches in five weeks to 26 inches above the ground. Between the blue and the red layers (the top of the latter now ten inches above the ground) there was little diminution (three inches) in thickness during the five weeks, but was subjected to a moderate increase in density (ten per cent). The red layer, now distinctly of porous crusty nature and only five inches thick had a density of 50 per cent. Below the bottom of the red was an uncolored layer of four inches, density 48 per cent. The bottom two inches were blue and of the same density (50 per cent) as on both January 3 and December 6. Dead leaves and grass on the ground-surface were blue from the coloring matter of the melting snow; the blued layer had been in contact with the surface for nearly two months, had lost two inches in thickness, but had not changed in density. At the conclusion of the examination, brown dye was sprinkled over the surface and also some brown-dyed sawdust was lightly scattered over the surface. The dyed surface was covered with a thin layer of snow to reduce the absorption of insolation of the dark particles.

Two storms in February (10 to 11 and 24 to 27) left about 25 inches of new snow, but this amount was insufficient even to maintain the depth of 57 inches on the ground found on February 1; on March 1 the depth was only 50 inches. Rain and melted snow formed 3.75 inches of precipitation between February 1 and March 1, a total of 32.37 inches since the snow first remained on the ground.

Because of the little snow or rain in February the next examination was not made until March 7; the depth on that date was 47 inches and water-content 21 inches. Again the same procedure was followed. The profile showed that the porous crust at 46 inches on February 1 was at 38 inches and had become impervious. The top nine inches of snow had a density of 47 per cent from the 4.2 inches of water, or in five weeks from rain, melt-water, and added weight of snow, the layer had increased in density some 27 per cent. The brown sawdust was found through a layer three inches thick, from 45 inches to 42 inches. That the crust was impervious can be seen in that the density of the next layer below, from 23 inches to 37 inches above the ground, averaged 39 per cent; it had increased only eight per cent in density. It was within this zone (between 23 inches and 28 inches) that the brown coloring was found just above the blue layer that had settled three inches since February 1. No brown dye could be detected below the blue. Under the blue layer was a 15-inch zone resting on the red crust, the top of which was now eight inches from the ground. The layer above the red had decreased one inch in five weeks, but the density had increased eight per cent (from 37 per cent to 45 per cent). The red layer, now two inches thick had a density of 48 per cent and the layer below 47 per cent. Blue was present in the last one inch above the ground.

Only two inches of snow fell (March 17) between February 27 and March 23, the date of the sixth and last visit, plus less than an inch of rain. Daily bright sunshine with high maximum temperatures brought an early decrease of the depth on the ground, a loss of the water-content in the column, and the destruction (by complete melting) of the impervious crust. However, there was no change in the density of the lower half of the column, and only a slight decrease in the upper half. The depth-on-the-ground dropped from 45 inches to 30 inches in 16 days and the water-content diminished from 21 inches to 13 inches. Though there had been a steady decrease in depth from late January, the water-content had shown an increase, albeit small, until March 7; from that date water-loss was rapid.

Under the unseasonally warm dry days, the snow-cover diminished so rapidly that on March 31 there was only 10 inches, the least amount on the ground on that date since before 1917-18, and 82 inches less than the average of 92 inches for that date.

Conclusions--The winter of 1940-41 was phenomenally poor in both snow and rain. Only the month of November had average snowfall. The latter part of December and all of January had sufficient snow to produce the normal rate of increase, but the small amount in the forepart of December and during all of February and March brought record small depths on the ground for February and March.

Early-season snow quickly reached its maximum density (approximately 50 per cent) from which the density did not vary appreciably in spite of age, meteorological sequence, or overburden. Even in late spring when melt-water penetrated freely to the bottom there was no important increase of density. All this is in agreement with conditions found during the preceding season. Maximum density this winter was found in an ill-formed crusty layer where the red dye was centered. Lateral sampling here showed a density of only 51 per cent.

The first cold weather came after a good snow-cover was present so the ground remained unfrozen. Melting proceeded from the bottom all winter, as shown by the decrease in thickness of the blue layer, from four inches on December 5, to one inch on March 7, to none on March 23. As a result, no melt-water froze in the lower part of the column throughout the whole season and this allowed good drainage. After the cover was greater than 30 inches in depth, the bottom six inches to ten inches of the column remained quite porous all winter.

A crust partially formed at the surface developed an impervious condition well below surface, a feature that was observed on the visit of March 7. Melt-water, together with rain carrying the brown dye, penetrated the then porous crust, before February 14, but after that date temperatures during the night were so low that freezing of melt-water made the crust impervious. The snow above the crust then increased in density to a higher figure than that just below the crust. On March 7 it was difficult to drive the sampler through the crust, which proved to be solid ice. This crust was the only impervious one to develop all winter although numerous porous ones were formed.

When there was a combination of an unfrozen ground-surface, no impervious crusts much below the surface, and daytime-maximum well above freezing, the snow-cover permitted good drainage of melt-water and loss of water-content despite temperatures at night below freezing. This was evident in November and again in March, for during both periods there was a marked divergence of the water-content in the snow-cover versus amount of rain and snow (melted) that fell. When daytime-maxima were below or not much above the freezing point, the water-loss was small, mainly melting from below and evaporation from the snow surface (see Table 1).

The lack of impervious crusts to form a glide-surface for the overlying snow, little rain, and the small amount of snow combined to produce an exceptionally avalanche-free winter; none of any consequence being reported and the task of keeping the road through the Pass was easy all winter.

Table 1--Precipitation, water-content, and loss of water-content in the snow-cover at Snoqualmie Pass

Item	Nov. 7-11	To Dec. 5	To Jan. 3	To Feb. 1	To Mar. 7	To Mar.23
Accumulated precipitation (rain and melted snow) in inches	2.52	11.14	19.58	28.58	33.11	34.18
Water-content in snow-cover (melted) in inches	2.50±	5.00	11.00	19.00	21.00	13.00
Total difference (loss) in inches	neg.	6.14	8.58	9.58	12.11	21.18
Water-loss between each observation in inches	....	6.00±	2.44	1.00	2.53	9.07

Reference

[1] P. E. Church, Ice-crusts and snow-settling at Snoqualmie Pass, season of 1939-40, Trans. Amer. Geophys. Union, 1940, pp. 928-932, 1940.

University of Washington,
Seattle, Washington

DISCUSSION

C. H. DIEBOLD (Forest Experiment Station, New Haven, Connecticut)--The use of dyes appears to offer an interesting method of studying snow-settling under certain conditions. An examination of the graph of daily maximum and minimum temperatures during the period of study shows that there were almost no thaws of longer than 36 hours' duration. In fact, daily freezing and thawing appears to have been typical. The depths of snow studied were for the most part in excess of 40 inches. I believe that these two factors were important in that the dyed crusts in general remained sharply separated until March.

Under conditions of a prolonged thaw such as that reported by Clyde in Utah State Agricultural Bulletin 231, somewhat different results were obtained. He reported that when fluorescein was placed on the snow-cover during clear warm weather it showed some well-defined water-channels through the snow. In general, however, the downward movement of moisture was more or less uniform through the entire mass. He also reported that fluorescein when placed on the snow-cover during a medium downpour of rain penetrated four feet of snow in five minutes. Thus it appears that the movement of dyes through the snow-blanket varies markedly under different conditions.

Clyde also reported that when fluorescein was placed on the snow when the air-temperatures were close to freezing the fluorescein remained in the snow-surface during the entire period that the temperature was at or below freezing. As the temperature rose, however, the coloring material began moving downward through the snow showing that the water in the snow-surface which carried the color was congealed and held in place until the higher temperatures melted it again. In Church's study it appears that despite daily temperatures above freezing during February the heat-waves were followed so closely by cold waves that little or no melting took place within the middle portions of the deep snow-mass until the middle of March. This result is similar to my snow-survey studies in New York that deep snow-blankets do not lose appreciable quantities of water during the early portion of break-up periods.

I believe from the results presented in Church's study that the application of heat-formulae to the rate of snow-melt will be exceedingly complex where the snow-cover is deep and the thaws are frequent but of short duration. For example, despite the fact that the bottom layer was at maximum density throughout the entire period and that thaws occurred daily from February 1 to March 7, only 2.5 inches of water were lost from a snow-mantle containing 20 inches of water.

A GAZETTEER OF ALASKAN GLACIERS

Wm. O. Field, Jr.

It has long been recognized that Alaska and the adjacent portion of Canada provide one of the finest regions in the world for the study of glaciers and the various problems connected with glaciation. The vast number of glaciers that exist in this region and the relative accessibility of many of them make it possible to conduct extensive studies without the need of organizing expensive expeditions. Almost every type and variety of glacier is well represented, with the exception of continental ice-sheets, which are now confined to the Polar regions. The main sources of information are contained in the accounts of the many scientists and travelers who have visited the Alaskan glaciers in the last 80 years. These are found in books, magazine articles, and reports in scientific publications, all of which, taken together, form a very substantial and significant contribution to the literature on the subject of glaciers. Other important sources of information are aerial photographs taken by the United States Navy and by Bradford Washburn, and the excellent topographic maps of the International Boundary Commission and the United States Geological Survey.

One of the most interesting phases of the subject and one for which Alaska perhaps offers the finest field of investigation, is the study of the variations in the size of glaciers. Within the past half-century astounding changes have taken place in this region. A few glaciers have disappeared completely, some have become stagnant, while others have either remained unchanged, or, indeed, have advanced into areas that have not been covered by ice for at least several centuries. Some of these changes have been carefully recorded but in altogether too many instances no observations have been made, with the result that a great deal of important information is missing.

To anyone who has attempted to make investigations in this field it is apparent that the great mass of existing source-material is widely scattered and that some of it is very obscure and therefore difficult to consult. Some of the useful references are merely incidental notes in accounts or reports dealing primarily with other subjects of investigation. Particularly is this so in the study of the variations of glaciers, where not uncommonly the casual descriptions of a traveler or his unpublished photographs may provide valuable evidence as to the condition of a glacier at a particular time. A further difficulty arises owing to the confusion in the identity and nomenclature of some of the glaciers, to the extent that authoritative maps sometime fail to agree.

In view of all this, there is a distinct need for a work of reference, or gazetteer, which would as far as possible list all the significant glaciers of Alaska and the adjacent portions of Canada, and would call attention to the studies and observations that have been made in the past. Such a gazetteer is now being compiled as one of the current projects of The American Geographical Society of New York in coordination with the program of the Committee on Glaciers of the American Geophysical Union and the International Commission of Snow and Glaciers. The work will summarize all available information on the glaciers of Alaska and northwest Canada and will list all the glaciers that have been named and described. In general, small unnamed summit and cirque-glaciers will be omitted, but all the known valley or alpine-glaciers of significance will be included. Each glacier will be described as completely as possible as to its main features, its size, direction of flow, area at different elevations, gradient, relationship to other glaciers, and the characteristics of its terminus. All known observations on each glacier will be indicated and its known variations summarized. If it is named, the origin of the name will be given and any confusion in its nomenclature will be pointed out and, if possible, clarified. There will also be a list of references to literature, maps, and photographs, both those which are published and those which, though unpublished, are available for examination. Much of this information will be assembled for the first time, the descriptions of many glaciers being based on topographic maps and photographs, especially photographs taken from the air.

The more important results which it is hoped to accomplish through this gazetteer are: First, to call attention to the excellent published studies of Alaskan glaciers which are now almost all over 25 years old; second, to encourage further studies of Alaskan glaciers and facilitate the task of reviewing the literature on the subject; third, to reveal new possible fields for investigation; fourth, to provide a basis for comparative studies of the dimensions and physical characteristics of a large number of glaciers and the variations which they have undergone, both such as have been observed in the last few decades, and such as are clearly indicated to have occurred in the last few thousand years; and fifth, it will make available a ready source of information that can be used as a basis for further information to the American public about the glaciers of Alaska.

It is expected that the section dealing with the glaciers of Southeastern Alaska and the adjacent part of Canada will be completed in 1941. Of this area Alfred H. Brooks [see 1 of "References" at end of paper] once wrote: "Southeastern Alaska is par excellence the region of the world in which to study glaciers." Though intensive studies have been made in certain localities, such as Glacier Bay, there are many glaciers which have never been studied or even visited by scientific parties, with the result that all that is known about them is what can be interpreted from maps and distant photographs taken in connection with the surveys. In all probability there are some glaciers whose existence has not even been reported.

It is hoped, further, in connection with the compilation of the gazetteer, that it will be possible to visit many of the glaciers of this region during the summer of 1941. Such field work will serve the purpose of bringing the data on the well-known glaciers up to date and will also make it possible to initiate investigations in localities not as yet visited for glacier-studies. Of the less accessible glaciers, additional aerial photographs will be secured in order to supplement existing information and for purposes of comparison to determine the nature of any changes in volume that may have occurred in recent years.

In conclusion, it may be said that a compilation of this kind is essentially for the use of students of glaciers. Since there is no standard pattern to be followed, the problems that arise concerning the best methods of presentation will have to be solved as the work progresses. For this reason it is hoped that those interested in this project will make such suggestions as they may consider pertinent. It is also urged that the editor be informed of any references to Alaskan glaciers which may occur in little-known publications or in reports primarily concerned with other subjects, so that they may be consulted and listed in the publication. In this way the gazetteer may be made as useful and as complete as possible within the limits of our present knowledge of the subject.

An example of the kind of information which the gazetteer will contain is given in the following condensed account of Ferguson Glacier, situated in the Hyder District of Southeastern Alaska. Although it is not a large or particularly significant glacier, it has been mapped and photographed and there are some observations of its variations. It is one of four ice-tongues in the valley of the West Fork of Texas Creek, a tributary of Salmon River, which in turn drains into the head of Portland Canal.

Ferguson Glacier (B 3 A 14)

(Each glacier is given an identification-number based on the latitude and longitude of its terminus. This is of use especially in the case of unnamed glaciers or where there is some confusion about the name)

All the information about this Glacier, unless otherwise stated, is derived from the United States Geological Survey map of Hyder District, Alaska, surveyed in 1924 and published in 1929.

Location--The terminus of Ferguson Glacier is in latitude 56° 03' north, longitude 130° 14' west. The Glacier enters the West Fork Valley from the south about 5-1/2 miles above the mouth of West Fork Creek and two miles below the head of the West Fork at Disappearing Lake. To the west is Hummel Glacier and in the adjoining valley to the east is Casey Glacier.

Description--Ferguson Glacier is the largest ice-tongue of the West Fork Valley, having a total length of about 3-1/2 miles and a maximum width of one-half mile.

Source--It has its source in several steeply-inclined cascading glaciers on the slopes of six peaks ranging in altitude from 5,801 to 6,350 feet. The upper sections of these tributary glaciers are mostly between 5,000 and 6,000 feet in elevation and are continuous over high divides with those of several other glaciers draining into nearby valleys.

Valley-glacier--These cascading tributary glaciers unite at elevations of 3,900 to 4,500 feet to form the main valley-glacier. From the 4,500-foot level the valley-glacier flows northward for about three miles to the terminus at an altitude of slightly below 2,300 feet. Its gradient is fairly uniform and varies between 12 and 16 per cent, but near the terminus it becomes somewhat steeper, suggesting that the Valley bears a hanging-valley relationship to that of the West Fork.

Terminus--According to the survey of 1924, the terminus is at an elevation of slightly below 2,300 feet, with a length of about 1,200 feet along its lobate front. Its position is at the entrance of the Valley only slightly above the level of the floor of the West Fork Valley and about 1,800 feet from West Fork Creek.

Area--As of 1924, the area of the surface of the Glacier at different levels is as follows:

Terminus to 3,000 feet	0.2 square mile	7 per cent of total area
3,000 to 4,000 feet	0.7 square mile	23 per cent of total area
4,000 to 5,000 feet	1.0 square mile	33 per cent of total area
Over 5,000 feet	1.1 square miles	37 per cent of total area
Total area	3.0 square miles	100 per cent of total area

In relation to these elevations, it appears from the available photographs that the summer névé-line probably does not rise above 4,000 feet and on an average may be nearer, 3,500 feet.

Variations--The only recorded observations of Ferguson Glacier are by A. F. Buddington [2] of the United States Geological Survey in 1923 and 1925. Of its variations he wrote: "Ferguson Glacier is retreating, and the old rough moraines extend in front of the present ice for half a mile or so, forcing the West Fork of Texas Creek to flow against the cliffs on the north side of the valley." He also reported that old lateral moraines were conspicuous along the margins of Ferguson Glacier 100 feet, or locally as much as 250 feet, above the level of the present lateral moraines.

A comparison of the Boundary-Survey Map of 1893-1895 with the United States Geological Survey Map made in 1924 suggests a possible retreat in that interval of as much as 500 feet. In any case it is clear from the photographs taken in conjunction with the Survey in 1924 that the ice then had vacated the area between the terminus and the creek in recent decades. The barren zone marking the position of the expanded-bulb terminus, which almost stretched across the Valley of the West Fork, was still very distinct. Only a little vegetation had begun to grow along its outer edge. Beyond this barren zone, so recently occupied by the ice, was mature forest marking unmistakably the limit of any ice-advance in at least several centuries, possibly much longer. This recent total retreat of the terminus is therefore somewhat less than the distance between it and the creek, which in 1924 was about 1,800 feet. There are no recorded observations since 1924.

As in the case of other glaciers in Southeastern Alaska and other parts of western North America it seems likely that this recent maximum position of the ice was preceded by a period during which the glaciers were much smaller and such a glacier as the Ferguson either disappeared or was reduced to a very small size at higher levels [3,4].

Name--The name Ferguson Glacier was probably in local use when Buddington first adopted it officially in the text of his report and on the accompanying map, U. S. Geological Survey [Bull. 773, p. 85, 1923, and map Plate I].

Miscellaneous--Buddington [5] states that the valley-part of Ferguson Glacier can be traversed to its upper end where there is a pass at an elevation of about 4,600 feet leading southward into the Valley of Thumb Creek. This route has been used by prospectors and miners, for it seems to be the best way of reaching the Valley of Thumb Creek, whose lower end is so narrow and precipitous as to be nearly impassable.

References--Reports: United States Geological Survey Bulletins 773, p. 85, 1925, and 807, p. 11, 1929. Maps: Ferguson Glacier is best shown on the United States Geological Survey topographic map (scale 1:62,500) entitled Hyder District, Alaska, surveyed in 1924 and issued as Plate I in United States Geological Survey Bulletin 807, 1929. It is also indicated on the maps of the preliminary International Boundary Survey of 1893-95, Sheet 7, and of the completed survey, Sheet 3, published in 1927. Photographs: Published photographs of United States Geological Survey Bulletin 807, Plate 8A, View of the terminus and lower part of the Glacier, taken by Buddington in 1925; Plate 9B, View of part of the upper portion of the valley-glacier and its tributaries, taken by Buddington in 1925. Unpublished photographs of United States Geological Survey, Alaskan Branch Collection, R. M. Wilson, Nos. 67 and 122. Views of the barren zone in front of Ferguson Glacier and the position of the terminus in relation to other topographic features, 1924.

References

[1] A. H. Brooks, Glacial phenomena of southeastern Alaska, U. S. Geol. Surv., Prof. Paper 1, p. 32, 1902.
[2] A. F. Buddington, Mineral investigations in southeastern Alaska, U. S. Geol. Surv. Bull. 773-B, p. 85, 1925.
[3] F. E. Matthes, Report of Committee on Glaciers, Trans. Amer. Geophys. Union, pp. 396-406, 1940.
[4] F. A. Kerr, Quaternary glaciation in the Coast Range, J. Geol., v. 44, pp. 681-700, 1936.
[5] A. F. Buddington, Geology of Hyder and vicinity, southeastern Alaska, with a reconnaissance of Chickamin River, U. S. Geol. Surv. Bull. 807, p. 11, 1929.

American Geographical Society,
New York, New York

A PROPOSED METHOD FOR CALCULATING STREAM-FLOW

O. E. Guthe and J. C. Owen

In recent studies of stream-flow determination from rainfall-records much emphasis has been placed on antecedent weather. The soil-moisture deficiencies that occur on a watershed as a result of weather preceding rainfall could be rather closely estimated if the amount of moisture lost by evaporation and transpiration between storms were known. Instruments designed to secure measurements of such losses are only now being perfected [see 5 of "References" at end of paper] and it was in anticipation of them that a proposed method has been developed for calculating contributions of runoff to stream-flow by reference to soil-moisture deficiencies at the beginning of rainfall. The details of the method are tentative. Only a brief outline of the procedure and of the results obtained is therefore presented in this paper.

Calculations were made on the basis of four-hour intervals and isochrones, or "time-contours," were used for determining the time-lag between the occurrence of runoff and its effect on discharge at the outlet of the watershed. Charts, or diagrams, showing the relationships of base-flow and channel-storage to total discharge were evolved for the rapid solution of the storage-equation. The rates of water-movement used in the procedure were based on a study of rainfall and stream-flow for the period from July, 1937, to August, 1938, and the depletion-curve was derived from the record of flow from 1929-1938.

After an analysis of the hydrologic characteristics of the watershed and the establishment of a single initial value for ground-water storage, a synthetic hydrograph was constructed for a

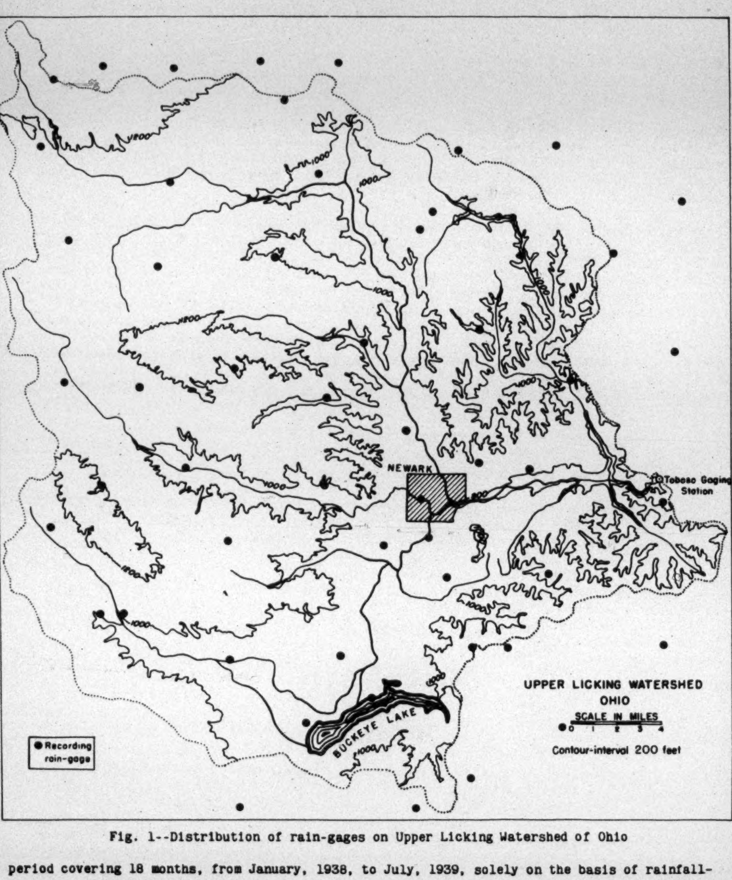

1200
1000
800
NEWARK
Toboso Gaging Station
BUCKEYE LAKE
UPPER LICKING WATERSHED
OHIO
SCALE IN MILES
0 1 2 3 4
Contour-interval 200 feet
● Recording rain-gage

Fig. 1--Distribution of rain-gages on Upper Licking Watershed of Ohio

period covering 18 months, from January, 1938, to July, 1939, solely on the basis of rainfall-data and calculated losses of moisture to the air without further reference to actual stream-flow.

Area of investigation--The method is an outgrowth of a study of rainfall-runoff relations on the Upper Licking Watershed of Ohio (Fig. 1). This watershed is 672 square miles in area. The gently rolling till plains to the west are separated from the hilly eastern part by broad flat terraces of glacial fill in the valleys of the Licking River and its tributaries. The unusual drainage-pattern with three major tributaries of nearly equal length combining to form the main stream 11 miles above the gaging-station at Toboso places the northern, western, and southern parts of the Watershed equally distant from the gaging-station. Approximately 50 recording rain-gages are operated in and immediately adjoining the area as part of the network of the Muskingum Climatic Research Center. Since July, 1937, isohyetal maps of 30-minute and four-hour amounts have been constructed for all storms occurring on the Watershed. Weekly sampling of farming operations and plant-growth was conducted during the growing seasons of 1938 and 1939.

The collected data were used in determining transpiration-rates.

Calculation of soil-moisture deficiencies--Pending measurements of moisture-loss from the ground to the air, the increase in soil-moisture deficiency during periods without rain was considered equal to the sum of calculated transpiration from plants and evaporation from the soil.

Estimates of the annual amount of moisture lost by transpiration from vegetation on the Watershed were based largely on yield, which experiments have shown to be closely related to the amount of water used in plant-growth [2]. For a given type of vegetation, the water used to produce a unit of yield was derived from experimental data [4] and was expressed in acre-inches. This value was adjusted for regional differences during the growing season in the opportunity for transpiration between the location of the experiments and central Ohio, and was then multiplied by the average yield for the Watershed during the year of maximum yields in Ohio from 1918-1937. The result was the annual amount of water used per acre under favorable conditions in central Ohio. (Yield-figures for 1938 would have been more satisfactory for correlation with growth-curves for that year, but they were not available when needed. Local reports indicated that yields of 1938 would be well above average.)

No attempt was made to compute the daily fluctuations in transpiration caused by variations in atmospheric conditions or by temporary reduction of available soil-moisture to the wilting-point. Over a longer period of time, however, the amount of transpiration is roughly proportional to leaf surface until maturity is approached, and leaf-surface has been shown to be correlated with plant-height [1]. Therefore, plant-height and stage of growth were used for computing the changing amounts of transpiration with changes in growth-development. The computed values of annual use of water were distributed throughout the period of plant-activity in accordance with appropriate average growth-curves obtained for 1938. By this means, the relations of average daily amounts of transpiration to height and stage of growth were approximated. To use corn as an example, Figure 2-A gives the average rate of corn-growth in the area in 1938 and the probable march of transpiration associated with that growth. By applying the computed value of annual transpiration to the area below the curve until harvest, the average daily rates of transpiration were secured and their relations to height and stage of growth are shown in Figure 2-B.

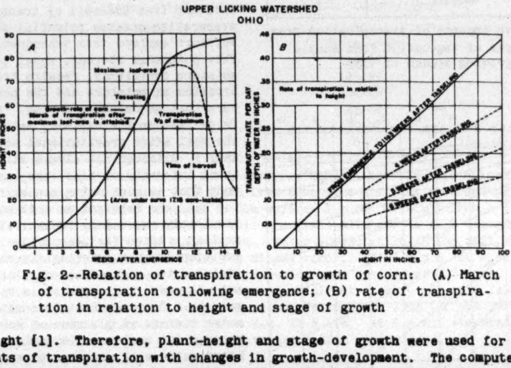


Fig. 2--Relation of transpiration to growth of corn: (A) March of transpiration following emergence; (B) rate of transpiration in relation to height and stage of growth

The varied character and extent of vegetal types gave diverse transpiration-rates for different periods in the various parts of the Watershed. Figure 3 indicates the distribution of transpiration through the growing season of 1938 from an area of 8.9 square miles surrounding a single rain-gage in the northwestern part of the Watershed. The relative contributions of each of five types of vegetation to the total transpiration from the area are also shown.

The basic rates of evaporation from the soil were obtained empirically from analyses of the rainfall- and runoff-relations of the Watershed, interpreted with reference to associated temperature and calculated transpiration-rates. From experimental evidence, it was assumed that the rate of evaporation from the soil decreases exponentially with time and that, on the average, opportunity for evaporation varies roughly with air-temperature. Shown graphically, the evaporation from the soil was plotted as the ordinate and the time in days as the abscissa (Fig. 4). Since losses to the air during the night are relatively slight, the time of evaporation and

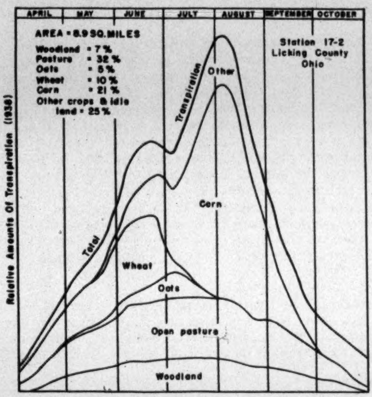


Fig. 3--Relative amounts of transpiration from different types of vegetation from sample area during growing season of 1938

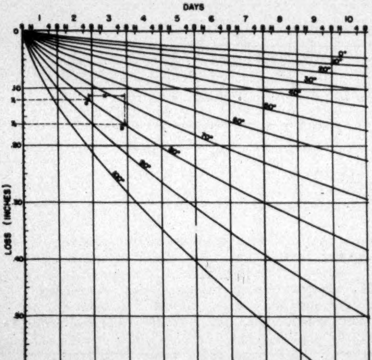


Fig. 4--Relation of evaporation from soil to temperature and time

transpiration was considered as extending from 8 a.m. to 8 p.m., with the period from noon to 4 p.m. being twice as effective as either of the other two periods. Taking the temperature at 10 a.m. as the approximate mean for the day, the temperature-factor was introduced as a family of curves. Moisture-loss through evaporation during a given time-interval was calculated by obtaining the value of previous loss by evaporation y_1; finding the intersection a of this value with the appropriate temperature-curve 80° F; moving down this curve a distance equivalent to the interval x; and obtaining the value of y_2. The difference, $(y_2 - y_1)$, was the evaporation for the interval. The amount of evaporation from the soil for a series of rainless days with varying mean temperatures was secured by following this procedure.

Determination of increments to stream-flow--The procedure outlined in this paper was based on the concept that the loss of moisture from the soil by transpiration and evaporation creates potential storage for moisture derived from subsequent rainfall. This potential storage, equal to the soil-moisture deficiency, results from the subtraction of moisture and the change in structure that accompanies drying. (Soil-moisture is defined as the residual water retained in the soil after gravitational water has drained away.) Although not always strictly true for short intervals of time, the assumption was made that as much water can be returned to the soil and retained as soil-moisture as was previously removed by transpiration and evaporation. After field-capacity is restored, additional water entering the soil is restricted to pores of non-capillary size and will be moved to lower levels by the force of gravity. This water will accrete to ground-water storage if the zone of aeration has reached its maximum water-holding capacity. Storm-water will continue to enter the soil as long as rainfall persists, but at a rate no greater than the capacity of the soil to receive it. When a condition of near-saturation exists in the soil, any rainfall in excess of the rate of accretion to ground-water storage is removed by surface-runoff or subsurface storm-flow. Since no attempt was made to differentiate between these two kinds of removal, the rates of accretion are not necessarily related to infiltration rates.

The first step toward the determination of increments to stream-flow was to distribute storm-water with respect to this concept of water-movement in the ground. The amount of water that fell in each four-hour period of rain was recorded by the gages. From this amount was deducted a value equal to the soil-moisture deficiency that had been accumulated in the soil by losses through evaporation and transpiration prior to the rain. If this value was exceeded by the rain, a further deduction was made to provide for accumulation of gravitational water within the soil. An apportioned amount of this accumulated water was assumed to accrete to ground-water storage during the succeeding four-hour period. (Determination of accretion-rates is explained in the next paragraph. The amount of gravitational water accumulated in the soil was considered double the rate of accretion to ground-water storage and had the effect of delaying accretion by four hours.) Any rainfall during a four-hour interval in excess of the stated amounts to be deducted to restore field-capacity and provide for accumulation of gravitational water for accretion to ground-water storage was classed as direct runoff. To allow for occasional intense storms during the summer months it was found advisable to consider rainfall above 0.4 inch in 30 minutes as direct runoff, irrespective of soil-moisture deficiencies. In cases where rain was insufficient to reduce soil-moisture deficiency to zero, evaporation from the soil began after the rain at the maximum rate and did not drop to the rate which applied just before the storm until the recently added soil-moisture was lost.

The four-hour rates of accretion to ground-water storage in the Upper Licking Watershed were established by analyzing a number of rises in base-flow at different times of the year and by relating the increases in ground-water storage to the areas and durations of the storms causing them. The volumes of these additions could be calculated from a tabulation of ground-water versus storage-discharge relations obtained, by four-hour intervals, from an integration of the depletion-curve from zero-flow. The depletion-curve was secured in a manner similar to that employed by W. B. Langbein [3] in his determination of a normal recession-graph by plotting one day's discharge against that of the following day. This procedure has the advantage of indicating storm-runoff more readily than does visual inspection of the hydrograph.

The rates of accretion were found to vary rather consistently with temperature:

Four-hour rate of accretion to ground-water storage	Temperature at 10 a.m. temperature
Inch	°F
0.10	70 and over
0.09	58-69
0.08	46-57
0.07	34-45
0.06	22-33
0.05	10-21
0.04	0- 9

To give a quantitative example of the procedure, assume that the soil-moisture deficiency at noon on a given day is 0.5 inch. Rainfall from noon to 4 p.m. was recorded as 0.3 inch. A moisture-deficiency of 0.2 inch remained in the soil at 4 p.m. Rainfall from 4 p.m. to 8 p.m. was 0.7 inch. This increment of rain reestablished field-moisture to full capacity and a difference of 0.5 inch remained to be distributed. Water-accumulation in the soil was estimated at 0.2 inch for the period, leaving 0.3 inch for direct runoff. From 8 p.m. to midnight accretion to ground-water storage was 0.1 inch. Rainfall during this period was 0.3 inch, of which 0.1 inch remained in the soil and 0.2 inch contributed to direct runoff. No rain fell from midnight to 4 a.m. and the rate of accretion to ground-water remained 0.1 inch for the period. The residual 0.1 inch passed to ground-water from 4 a.m. to 8 a.m. At 8 a.m., evaporation from the soil began at a maximum rate for the day, and transpiration was renewed.

After determining the direct runoff at each precipitation-station on the Watershed, these values were plotted at their respective locations on a map of the area. Previously the Watershed had been divided into four time-zones by isochrones having 4-, 8-, and 12-hour values on the basis of the observed lag between the occurrences of small isolated storms producing increases in flow and the resultant rises at the gaging-station. (Lag was measured from the centers of mass of rainfall and discharge. The values of the isochrones were sufficiently large to obviate adjustment for variations in the rates of flow.) The time required for the direct runoff to affect discharge at the gaging-station was indicated by the time-zone in which runoff occurred. The area of a time-zone multiplied by the average depth of direct runoff within it gave the volume of direct runoff from that zone. These contributions to channel-storage were tabulated in the time-sequence of their initial effect on discharge at the gaging-station as indicated in columns (13) and (14) of Table 1, which gives a sample computation of discharge for the period March 4-7, 1938. Column (15) shows the successive four-hour increments to channel-storage at the gaging-station from direct runoff from all contributing parts of the Watershed.

Accretion to ground-water storage was assumed to be reflected at the gaging-station in increased base-flow relatively soon after its occurrence. The same isochrones used for direct runoff were applied for calculating ground-water accretion. The increments to ground-water storage created by these accretions were also tabulated in the sequence of their resultant initial effect on base-flow at the gaging-station as shown in columns (3) through (9).

Construction of the hydrograph--The first step in the synthesis of the hydrograph was to determine an initial value of ground-water storage. By the use of ground-water storage-discharge tables this value was obtained from a base-flow selected from the record of stream-flow after a rain sufficiently great to reduce soil-moisture deficiencies throughout the watershed to zero. No further reference was made to the actual hydrograph.

Starting with the base-flow associated with this selected ground-water storage, successive values of base-flow were taken directly from the depletion-curve until an addition to ground-water storage occurred. Then the four-hour increment to storage would be added and the base-flow for the increased storage subtracted to give the new value for ground-water storage four hours later. This procedure was followed until storm-contributions to ground-water storage ended. Succeeding base-flow values were obtained by again referring to the depletion-curve.

The conversion of increments of direct runoff into channel-storage and discharge from channel-storage was made by the use of charts of relations of channel-storage to discharge, read with reference to computed values of base-flow. (Channel-storage was considered the excess of inflow over outflow that was built up by increments from direct runoff.)

The charts were based on a study of several rises in the hydrograph. By use of the depletion-curve previously obtained, the recession-sides of these rises were analyzed to secure the values for discharge from a given channel-storage in association with different values of base-flow. For each segment of the hydrograph shown in Figure 5-A, the channel-storage, Sc, has the same value. The values of ground-water storage, Sg, differ for each segment as do the associated four-hour values of base-flow, dg. When the three sets of values for channel-storage discharge, dc, and base-flow were plotted on the base shown in Figure 5-B, three points--a_1, a_2, and a_3--were secured. When connected, these gave a channel-storage curve for the selected value. After

Table 1 --Sample computation of 4-hour discharge at Toboso, Ohio

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)
Date	Time	Accretion to ground-water storage						Increments to ground water	Ground-water storage	Base-flow	Gage-height of base-flow	Direct run-off		Increments to channel storage	Channel storage	Discharge from channel storage	Total discharge (11)+(17)	Total gage-height
		1000 cu.ft.	1000 cu.ft.	1000 cu.ft.	1000 cu.ft.	1000 cu.ft.	1000 cu.ft.	1000 cu.ft.	1000 cu.ft.	1000 cu.ft.	Feet	1000 cu.ft.	1000 cu.ft.	1000 cu.ft.	1000 cu.ft.	1000 cu.ft.	1000 cu.ft.	Feet
Mar. 4	N - 4	.....	.....	.....	.....	.....	.....	.....	1442439	11553	3.24	.....	.....	.....	.....	.....	11553	3.24
	4 - 8	*[1]	.....	.....	.....	.....	.....	.....	1430886	11427	3.23	.....	.....	.....	.....	.....	11427	3.23
	8 -Mt	.....	*	.....	.....	.....	.....	.....	1419459	11302	3.21	.....	.....	.....	.....	.....	11302	3.21
Mar. 5	Mt- 4	550	.....	*	.....	.....	.....	550	1408707	11176	3.19	.....	.....	.....	.....	.....	11176	3.19
	4 - 8	60	1970	.....	*	.....	.....	2030	1399561	11082	3.17	.....	.....	.....	.....	.....	11082	3.17
	8 - N	.....	295	.....	.....	*	.....	295	1388774	10957	3.16	*	.....	.....	.....	.....	10957	3.16
	N - 4	.....	.....	375	80	.....	*	455	1378272	10837	3.14	1000	.....	1000	1000	463	11300	3.21
	4 - 8	*	.....	215	.....	170	13200	13585	1381020	10866	3.14	28900	*	28900	29437	4334	15200	3.73
	8 -Mt	8310	*	.....	.....	245	33960	42515	1412669	11239	3.20	88240	8250	96490	121593	13861	25100	4.88
Mar. 6	Mt- 4	27950	13200	*	.....	.....	50920	92070	1493500	12123	3.32	26660	10380	37040	144772	17377	29500	5.32
	4 - 8	47620	35680	9900	*	.....	6320	99520	1580897	13166	3.40	.....	21910	21910	149305	19034	32200	5.56
	8 - N	6320	52000	26760	9680	*	.....	94760	1662491	14076	3.58	.....	5530	5530	135801	18924	33000	5.63
	N - 4	.....	6320	39000	26240	2700	.....	74260	1722675	14765	3.67	.....	.....	.....	116877	17235	32000	5.54
	4 - 8	.....	.....	4740	31950	1635	.....	38325	1746235	15064	3.71	.....	.....	.....	99642	15036	30100	5.45
	8 -Mt	.....	.....	.....	4140	355	.....	4495	1735666	14932	3.69	.....	.....	.....	84606	13068	28000	5.17
Mar. 7	Mt- 4	.....	.....	.....	.....	.....	.....	.....	1720734	14756	3.67	.....	.....	.....	71538	11244	26000	4.97
	4 - 8	.....	.....	.....	.....	.....	.....	.....	1705978	14580	3.65	.....	.....	.....	60294	9720	24300	4.80
	8 - N	.....	.....	.....	.....	.....	.....	.....	1691398	14404	3.63	.....	.....	.....	50574	8296	22700	4.63
	N - 4	.....	.....	.....	.....	.....	.....	.....	1676994	14237	3.60	.....	.....	.....	42278	7163	21400	4.48
	4 - 8	.....	.....	.....	.....	.....	.....	.....	1662757	14076	3.58	.....	.....	.....	35115	6024	20100	4.33
	8 -Mt	.....	.....	.....	.....	.....	.....	.....	1648681	13915	3.56	.....	.....	.....	29091	5285	19200	4.23
Mar. 8	Mt- 4	.....	.....	.....	.....	.....	.....	.....	1634766	13753	3.54	.....	.....	.....	23806	4447	18200	4.11
	4 - 8	.....	.....	.....	.....	.....	.....	.....	1621013	13592	3.52	.....	.....	.....	19359	3808	17400	4.02
	8 - N	.....	.....	.....	.....	.....	.....	.....	1607421	13431	3.50	.....	.....	.....	15551	3269	16700	3.92
	N - 4	.....	.....	.....	.....	.....	.....	.....	1593990	13278	3.47	.....	.....	.....	12282	2722	16000	3.83
	4 - 8	.....	.....	.....	.....	.....	.....	.....	1580712	13129	3.46	.....	.....	.....	9560	2271	15400	3.75
	8 -Mt	.....	.....	.....	.....	.....	.....	.....	1567583	12981	3.44	.....	.....	.....	7289	1919	14900	3.69
Mar. 9	Mt- 4	.....	.....	.....	.....	.....	.....	.....	1554602	12833	3.42	.....	.....	.....	5370	1467	14300	3.61
	4 - 8	.....	.....	.....	.....	.....	.....	.....	1541769	12684	3.39	.....	.....	.....	3903	1216	13900	3.56
	8 - N	.....	.....	.....	.....	.....	.....	.....	1529085	12536	3.38	.....	.....	.....	2687	964	13500	3.51
	N - 4	.....	.....	.....	.....	.....	.....	.....	1516549	12395	3.35	.....	.....	.....	1723	705	13100	3.45
	4 - 8	.....	.....	.....	.....	.....	.....	.....	1504154	12259	3.34	.....	.....	.....	1018	541	12800	3.41
	8 -Mt	.....	.....	.....	.....	.....	.....	.....	1491895	12123	3.32	.....	.....	.....	477	377	12500	3.37
Mar.10	Mt- 4	.....	.....	.....	.....	.....	.....	.....	1479772	11986	3.30	.....	.....	.....	100	100	12086	3.31
	4 - 8	.....	.....	.....	.....	.....	.....	.....	1467786	11850	3.29	.....	.....	.....	0	0	11850	3.29

[1] Asterisk (*) indicates time of rainfall. Below asterisks are the distributed increments to storage from specified rain.

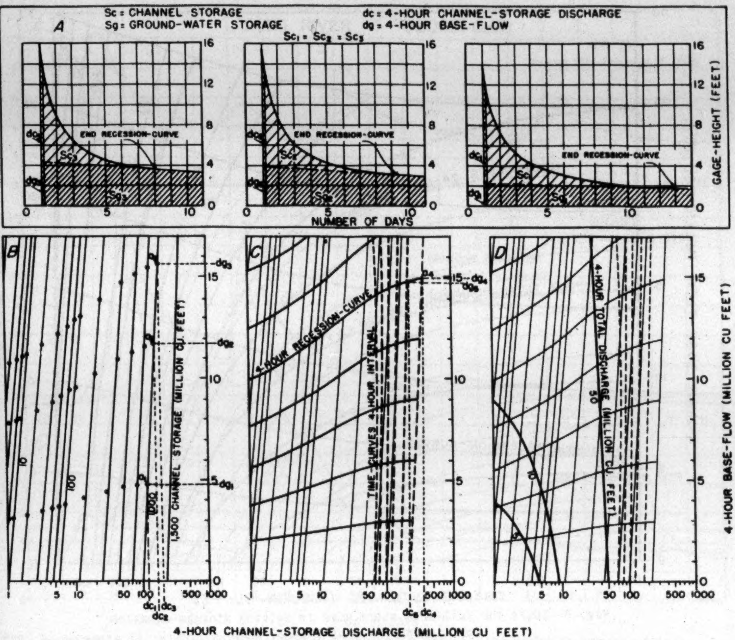


Fig. 5--Construction of chart: (A) Relation of channel-storage to discharge; (B) construction of channel-storage curves; (C) construction of recession and 4-hour time-curves; and (D) construction of total-discharge curves

plotting curves for several values of channel-storage, it was found that they formed a family of curves approximating a logarithmic spacing.

Another family of curves indicating successive four-hour discharges from a given channel-storage and base-flow were superimposed on the channel-storage curves (Fig. 5-C). Points for the construction of these curves were secured as follows: The intersection, a_4, of an assumed base-flow, dg_4, with some curve of channel-storage, preferably the highest value plotted, gave the four-hour discharge from channel-storage, dc_4, associated with the assumed base-flow and channel-storage; by subtracting this discharge from the original channel-storage, the value of the channel-storage at the end of the four hours was obtained; base-flow, dg_5, at the end of that interval, was taken from the depletion-curve of base-flow. These new values gave the discharge from channel-storage, dc_5, for the next four-hour period. By continuing the procedure until the channel-storage was reduced to a negligible amount, a series of points was obtained that was used in drawing a recession-curve that gave the successive discharges from the original value of channel-storage as associated with the base-flow value, dg_4. Other beginning values of base-flow were then chosen and the procedure was repeated. Points of equal time-interval were connected to give the four-hour-interval time-curves (Fig. 5-C).

A fourth family of curves was plotted in order that the four-hour total discharge from a given channel-storage and base-flow could be read directly from the chart. Each curve was obtained by connecting a series of points plotted so that the sum of the coordinates of each point equaled a single value of total discharge (Fig. 5-D).

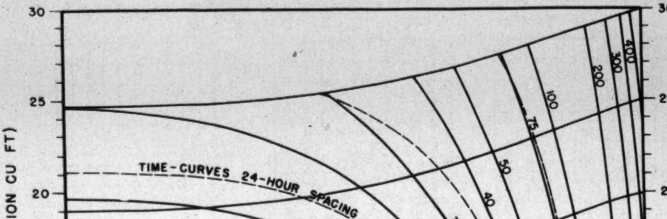


Fig. 6--Chart for full-area storm used in solving storage-equation for Licking River at Toboso, Ohio

To facilitate the use of these curves, a new base was constructed with values of channel-storage replacing those of channel-storage discharge on the abscissa but with values of base-flow being retained on the ordinate (Fig. 6). Three families of curves were then transferred to this new base by replotting. The first consisted of segments of the four-hour recession-curve; the second was composed of time-curves spaced at four-hour intervals, although only the 24-hour spacings are shown in Figure 6; and the third was made up of single-valued curves of four-hour total discharge. Because discharge-characteristics change with the area of the contributing storm and its location of the Watershed, several charts of this construction were prepared for full-area and different types of partial-area storms.

In applying the appropriate chart, the first increment from direct runoff from a given storm was considered channel-storage for the interval in which it occurred. By taking this value and the value of base-flow for the interval, a point was located on the chart that gave the total discharge for the period [column (18) of Table 1]. The discharge from channel-storage [column (17) of Table 1] was obtained by deducting the base-flow. Assuming for the moment no further increment from direct runoff, this discharge subtracted from the initial channel-storage would give the value of channel-storage for the succeeding interval. Any increment during this second interval was added to the value thus obtained to give the new value of channel-storage for the second interval [column (16) of Table 1]. The next point on the chart was located by relating this value to the base-flow for the interval. This procedure was continued until there were no further increments to channel-storage or ground-water storage. From then on, the recession-side of the hydrograph was obtained from the chart by taking the successive four-hour values of total discharge [column (18), after 4 a.m., March 7, of Table 1] from the appropriate recession-curve. When channel-storage became negligible, the hydrograph was extended by reverting to the base-flow values taken from the depletion-curve.

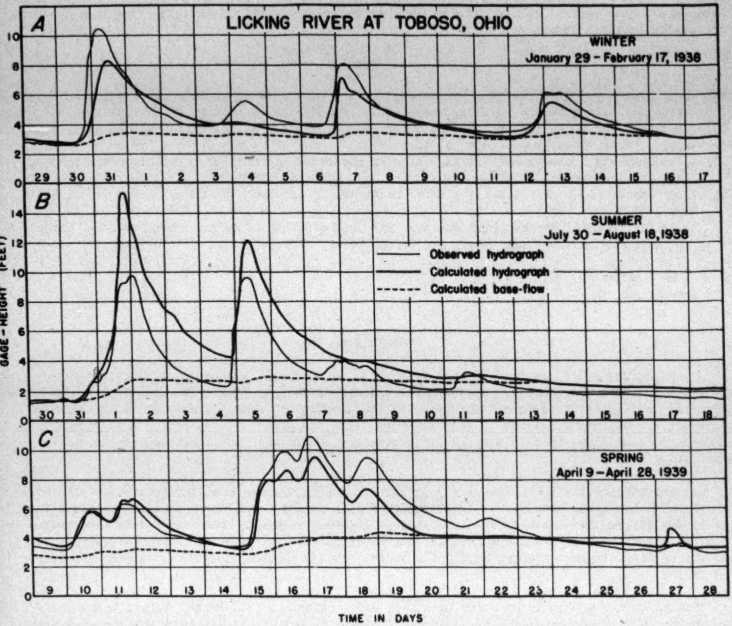


Fig. 7--Segments of calculated and observed hydrographs for Licking River at Toboso, Ohio: (A) From January 29-February 17, 1938; (B) from July 30-August 18, 1938; and (C) from April 9-28, 1939

The synthetic hydrograph was constructed from total discharge-values converted to gage-height [column (19) of Table 1] by the use of appropriate rating tables. In Figure 7, portions of the computed hydrograph for the Licking River at Toboso are compared with the observed hydrograph.

Conclusion--When the assumed values of moisture-losses to the air are replaced by measured losses, closer agreement can be expected between computed and observed hydrographs. It now appears that calculated losses to the air during the summer months are too low, as suggested by excessive direct runoff. Part of this excess may be credited to interception, which was not specifically considered, but it cannot be charged to insufficient accretion to ground-water storage. Following summer rises, calculated base-flow was slightly greater than observed base-flow, but this discrepancy was not cumulative since the base-flow hydrographs were essentially the same at the end of 17 months. Inasmuch as no adjustments were introduced for snow-accumulation and freezing, minor differences between the hydrographs should be expected for the winter months. The similarity in the timing and shapes of the rises of the computed and observed hydrographs is especially noteworthy because no reference to the actual stream-flow was made after an initial value of ground-water storage was secured and the parameters used in the procedure were not changed or adjusted to obtain better fits for individual rises.

A relatively dense network of rain gages and a knowledge of the distribution and changing character of the vegetation is needed for the application of the method in its present form. It is believed that additional research will yield a simplified technique that can be used for watersheds with fewer existing data. It may then be possible to evaluate the effects of major land-use changes on stream-flow from large watersheds and to extend the stream-flow record in areas where only a short record of flow has been secured but adequate rainfall and land-use data are available for a longer period.

References

[1] W. E. Bruner and J. E. Weaver, Size and structure of leaves of cereals in relation to climate: A study in crop ecology, Nebr. Univ. Studies 23 (3, 4), pp. 1-37, 1923.
[2] J. S. Cole and O. R. Mathews, Use of water by spring wheat on the Great Plains, U. S. Dept. Agric., Prof. Paper Bull. 1004, 33 pp., 1923.
[3] W. B. Langbein, Some channel-storage studies and their application to the determination of infiltration, Trans. Amer. Geophys. Union, pp. 435-445, 1938.
[4] H. L. Shantz and L. N. Piemeisel, Water requirements of plants at Akron, Colorado, J. Agric. Res., v. 34, pp. 1093-1190, 1927.
[5] C. W. Thornthwaite and Benjamin Holzman, The determination of evaporation from land and water surfaces, U. S. Mon. Weath. Rev., v. 67, pp. 4-11, 1939.

Soil Conservation Service,
Washington, D. C.

DISCUSSION

F. F. SNYDER (U. S. Weather Bureau, Washington, D. C.)--The authors have described an extensive study of a procedure for defining the relation between rainfall and runoff along lines which are believed to be fundamental. A brief statement of the basic concept is that existing soil-moisture or the deficiency in soil-moisture fixes the amount of runoff for a given storm and that soil-moisture is determinable if evaporation and transpiration between storms can be measured or computed.

An outstanding feature of the study is that transpiration was computed from basic data with no reference to stream-flow. The significance of this item is somewhat limited by the fact that the values of computed evaporation were based on observed rainfall- and runoff-data interpreted with reference to temperature and calculated transpiration. The total loss (sum of evaporation and transpiration) was therefore based on a study of the observed differences between rainfall and runoff.

The study represents an enormous amount of detailed work mainly as the result of subdividing the Basin into approximately 50 sub-areas for each of which detailed calculations were made. It is believed that further investigations would develop means of eliminating the need for so many subdivisions.

One of the basic assumptions adopted by the authors is so different from the usual concept of the same situation that special attention and future consideration should be given to the point involved. According to the procedure described in the paper no runoff is available with the exception of rain falling at a rate in excess of 0.40 inch per half-hour until the total soil-moisture deficiency is satisfied after which time all rainfall is apportioned to ground-water and direct runoff. This assumption would be questionable even if the number of subdivisions were greater than that used by the authors.

Another interesting feature of the procedure is the determination of accretions to ground-water storage on a basis of temperatures. The writer has had occasion to note a temperature-effect on both ground-water and surface-runoff, but never tested the possibility that temperature alone could be used as a direct key to ground-water recharge.

The following statements represent the qualitative results of the writer's experiences in analyzing ground-water recharge. (1) Other things being equal, the greater the total runoff, the greater will be the ground-water runoff. (2) For the same amount of total runoff, ground-water recharge is greater in the winter than in the summer. (3) There is a maximum value to the amount of recharge possible from a storm of a given duration. Not all of these are compatible with the assumption followed by the authors.

The procedure as described in the paper introduces the effect of ground-water recharge on discharge at the outflow-station sooner than is usually believed possible. With the exception of a four-hour lag the effect from ground-water recharge appears as rapidly as that from direct runoff. This particular item is not too important since the handling of ground-water discharge after the amount of recharge has been determined is mainly a problem of adaptation to the general procedures being followed.

The method of synthesis of the hydrograph from the calculated amounts of runoff gave quite satisfactory results as evidenced by a comparison of the timing and shapes of the calculated and observed rises illustrated on Figure 7. The quantitative agreement for the periods presented is not as satisfactory as could be desired in view of the extreme refinement of the calculations. It is believed that this is more an indication of the need for simplification and adjustment of the particular approach being followed than it is an indication of any weakness in the basic concept of the problem.

G. W. MUSGRAVE (Soil Conservation Service, Washington, D. C.)--To me the fact that this paper has much of merit in it is demonstrated by the excellent agreement of the authors' computed and calculated curves in so far as the time-element is concerned. In so far as volumes are concerned, perfect agreement can never be expected, because antecedent rains have other effects upon natural soils than merely that of filling voids with water.

In a medium comprised of fine quartz-grains in which there are no colloids and in which the individual grains are fully stable it might be expected that the addition of a given quantity of water would result in a reduction of its capacity by like amount and that conversely the withdrawal of given increments of water would provide a like amount of new space.

In natural soils, however, antecedent rains have very definite effects upon soil-structure. The impact of the falling drop disintegrates surface-aggregates, disperses soil-particles permitting infiltration of solid material to points of constriction within the soil-profile and the water added usually causes swelling. The withdrawal by evaporation or transpiration-processes of a given amount of water does not immediately return the soil to the same physical state which prevailed at the earlier though identical moisture-content. This is a plausible reason for the seasonal discrepancies in the author's actual and computed curves.

In brief, we may expect relationships between infiltration and content of water in the soil-profile to be direct only in so far as the water has done no more than fill voids. On the other hand, in so far as antecedent rain has modified the soil-structure, particularly at the surface, the new structural condition rather than the moisture-content becomes the important factor controlling infiltration.

VIRTUAL CHANNEL-INFLOW GRAPHS

Robert E. Horton

Basis of virtual channel-inflow graph--What may be called a "virtual channel-inflow graph" can in many cases readily be derived from certain properties of the channel-outflow graph (for the sake of brevity this will be designated a virtual-inflow graph or V-I graph).

If a given channel-inflow graph is transposed in time so that the channel-inflow begins simultaneously with the outflow at a given station, then the following four relationships will hold true between the transposed channel-inflow graph and the outflow-graph which it produces (see Fig. 1):

(1) Channel-inflow ends at the point of contraflexure P_2 on the recession side of the channel-outflow graph.

(2) The inflow- and outflow-graphs have a common point at the maximum outflow.

(3) Channel-inflow begins at the beginning of channel-outflow.

(4) The areas under the channel-inflow and outflow-graphs are equal and each represents the total surface-runoff.

These four rules make it possible to construct a triangular or trapezoidal channel-inflow graph which will give the same total runoff, the same maximum runoff at the same time, and will have rising and recession-characteristics nearly the same as those produced by the actual channel-inflow graph. This may be called the virtual channel-inflow graph. Its accuracy in any given case can readily be checked by using it as a basis for computing the channel-outflow graph in the manner later described.

The triangle abd (Fig. 1) meets the requirements listed. The point d is under the point of recession-contraflexure P_2. The inflow recession-line starts at b and passes through the outflow-crest c. The rising side of the V-I graph starts at beginning of runoff at a and is drawn to such a point b that the area abd is equal to the area A under the outflow-graph, excluding ground-water flow. Since the time base b = ad, the crest-height or altitude of the triangular V-I graph is given by the equation

$$A = bI_g/2 \tag{1}$$

or

$$I_g = 2A/b \tag{2}$$

where I_g is the maximum point on the V-I graph.

In addition to the four requirements listed, the V-I graph for a normal single-crested stream-rise has two other characteristics:

(a) The crest of the V-I graph occurs at about the same time as the point of contraflexure P_1 on the rising side of the outflow-graph. This requirement is approximately met by the triangle abd (Fig. 1).

(b) While the rising side of the outflow-graph is nearly always steeper than the recession-side, the reverse is usually true for a channel-inflow graph. For the latter the slope of the rising side is more gradual because of the fact that in the early stages of surface-runoff a large part of the rainfall-excess goes to build up surface-detention, and surface-runoff can only occur at the rate determined by the depth of surface-detention, which sustains the overland-flow. After rainfall-excess ends, the remaining channel-inflow is derived solely from surface-detention and this is quickly exhausted by the combined effects of surface-runoff and infiltration. Hence the V-I graph drops off rapidly, the slope of the recession-side is steeper than that of the rising side, and the recession-interval on the channel-inflow graph is less than the interval of rise, as shown by the graph abd (Fig. 1).

Limiting forms of virtual-inflow graphs--The triangular V-I graph abd (Fig. 1) is not, however, the only form of channel-inflow graph which meets the four fundamental requirements. Neglecting the two secondary requirements, any figure having a base ad and a recession-side which falls on the line bcd and which has an area A equal to that of the outflow-graph, meets the four primary requirements for a V-I graph. Since the outflow-rate cannot exceed the inflow-rate, the altitude of the inflow-graph cannot be less than that of the outflow-graph. Also the rising side ab must either be vertical or slope upward to the right.

In the limiting (but improbable) case where the rising side of the inflow-graph is vertical, the four requirements are met by a trapezoidal inflow-graph, such as aefd. If a is the top width of a trapezoidal V-I graph, then

$$A = I_t(a + b)/2 \tag{3}$$

where I_t is the crest-height for the trapezoidal graph. Since the maximum outflow-rate cannot exceed the maximum inflow-rate, the minimum possible value of I_t is the maximum outflow-rate, q_g.

If S is the slope of the recession-side of the V-I graph, in terms of time per unit-difference of vertical height or inflow-rate, then

$$S = (b - t_g)/I_g \tag{4}$$

where t_g is the crest-time on the triangular V-I graph, measured from the point a.

In the limiting case of a vertical rise, the trapezoidal graph must have a height I_t such that

$$[b + t_g + S(I_g - I_t)]I_t/2 = A \tag{5}$$

or

$$[CI_t - (SI_t)^2]/2 = A \tag{6}$$

where $C = (b + t_g + SI_g)/2$.

Hence

$$I_t = C/S + \sqrt{C^2/S^2 - 2A/S} \tag{7}$$

from which the height of the trapezoidal graph of minimum crest-height can be determined. This is shown by the graph aefd of Figure 1.

Any V-I graph having a form between the limiting cases of the triangle abd and the trapezoid aefd meets the four primary requirements. Channel-inflow, however, never begins abruptly at full intensity and the rising side of the inflow-graph is never vertical. The most probable form of the V-I graph is that having a crest somewhere between the crest b of the triangular graph and the crest ef of the minimum trapezoidal graph. The mean of the limiting triangular and trapezoidal forms is not, however, the most probable or most usual form of inflow-graph. A study of many inflow-graphs shows that for a rise produced by a single continuous period of

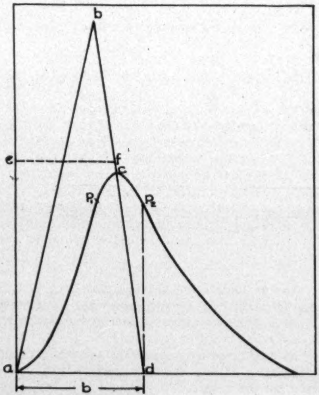


FIG. 1 - VIRTUAL CHANNEL-INFLOW GRAPH

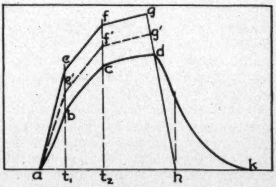


FIG. 2 - CONSTRUCTION OF POLYGONAL V. I. GRAPH

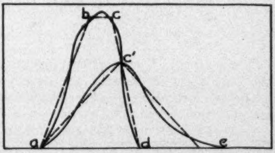


FIG. 3 - EFFECT OF USE OF V. I. GRAPHS BOUNDED BY STRAIGHT LINES

rainfall-excess, the inflow-crest approaches the simple triangular form (abd, Fig. 1) so closely that in most such cases this form may be used without sensible error.

The method as thus far described applies to a normal outflow-graph such as is produced by a single period of rainfall-excess on the drainage-area.

In case of a double-crested or multiple stream-rise, the equivalent channel-inflow graph for each rise should be determined separately. The channel-outflow for each rise can easily be separated in most cases, since the recession-arc for the part of the first rise which continues after the second rise begins, can be obtained by transferring the recession-arc for the second rise to the first rise, since the quantity of channel-storage and the relation of channel-storage to outflow is the same for the same outflow-rates in both cases. The graph of the second rise can then be platted separately and the equivalent channel-inflow graph determined therefrom.

It will be noted that the V-I graph always begins at the beginning of the rise at the gaging-station. This is one reason why it is called a virtual inflow-graph. It is the channel-inflow graph displaced in time so that it begins when the outflow-rise begins. It therefore eliminates the vexed question of time of channel-transit. The actual inflow-graph may of course begin and end earlier.

The outflow-graph represents the channel-inflow graph as modified by channel-storage but this modification cannot begin until the channel-storage becomes effective at the outlet or gaging-station. The V-I graph is in effect the same as if the channel-storage was all transferred to a reservoir just upstream from the gaging-station, the reservoir having the same capacity and the same stage-outflow relation for both rising and receding stages as the actual channel-storage.

The V-I graph represents correctly the sequence and magnitude of channel-inflow but not its actual time of occurrence. This statement is of course subject to the qualification that the V-I graph is made up of straight lines instead of having the more-or-less curved outlines of the channel-inflow graph.

Effect of form of outflow-graph on form of inflow-graph--While an outflow-graph of normal form can be accurately reproduced from a triangular or trapezoidal inflow-graph, it is obvious that sudden variations of rain-intensity may produce outflow-graphs that are not normal and inflow-graphs that are not triangular or trapezoidal. The form of the inflow-graph is reflected in that of the outflow-graph.

Referring to Figure 2, there were evidently abrupt changes of inflow-intensity at times t_1 and t_2. If, now, a line aefg is drawn, composed of segments having slopes proportional to those of the corresponding segments of the outflow-graph, this line can be swung to the right or left until it is adjusted to such a position ae'f'g'h that the area under it equals the area abcdk. This will be a close approximation to the channel-inflow graph.

Effect of use of triangular instead of curvilinear graphs--The actual channel-inflow graph is made up of curvilinear surface-runoff graphs for individual sub-areas and has curved boundaries. That these boundaries depart little from the triangular or trapezoidal form is easily seen from Figure 3. The actual graph must start at a, pass through c' and end at d, and have the same area as the triangular or trapezoidal graph; also it must be such that the channel-storage is the same at the outflow-crest time c'. Hence the excesses and deficiencies of area under the true and linear graphs must balance between a and c', also at c' and again at d. This requirement permits of but small departures of the curvilinear graph from the triangular or trapezoidal graph and vice versa, and these departures are alternately positive and negative and have little effect on the computed outflow-graph.

Determination of channel-storage by the use of virtual-inflow graphs--Thus far proof of the validity of the V-I graph rests solely on the fact that it meets the four primary requirements fixed by the hydraulic characteristics of the outflow-graph. More satisfying proof of the validity of the V-I graph is obtained by comparing actual outflow-graphs with those derived from the V-I graphs.

Channel-storage during recession, after surface-runoff or channel-inflow ends, can easily be determined by the method developed by the author [see 1 of "References" at end of paper]. Since there is no inflow, the channel-storage at any given point on the net recession-graph subsequent to the point P_2 (Fig.1) must necessarily be equal to the total subsequent channel-outflow. Hence the channel-storage can be obtained by summation backward of the area under the recession-curve of the outflow-graph. This method cannot be applied during rising stages when there is inflow. During channel-inflow the volume of channel-storage is the difference between the mass-inflow and the mass-outflow.

For hydraulic reasons channel-storage for a given outflow-rate is usually greater during rising than during receding stages. Heretofore there has been no simple or satisfactory method for determining channel-storage during rising stages, since this determination requires the use of both the channel-inflow and the channel-outflow graphs. The V-I graph supplies the requisite inflow-graph, and the channel-storage and storage-outflow relation can be determined therefrom for rising stages by starting at the beginning of the rise and determining the difference between mass-inflow and mass-outflow down to the end of successive time-increments. Platting these quantities in terms of the observed outflow-rates gives a graph of the channel-storage-outflow relation for rising stages. Table 1 contains details of the computation of channel-storage for both rising and receding stages for the hydrograph shown on Figure 4.

To determine channel-storage for rising stages after the triangular V-I graph is derived, a series of time-intervals is set down from the beginning of the rise, as shown in column (2) of

TABLE 1 - COMPUTATION OF CHANNEL-STORAGE — TIOGA RIVER NEAR ERWINS, N.Y. - RISE OF JULY 8, 1935

Date	Time	Outflow	Inflow	Diff. (4)-(3)	Mean	Δ Storage	Σ Channel Storage	Date	Time	Outflow	Inflow	Diff. (4)-(3)	Mean	Δ Storage	Σ Channel Storage
		c.s.m.	c.s.m.	c.s.m.	c.s.m.	C.F. PER S.M.	C.F. PER S.M.			c.s.m.	c.s.m.	c.s.m.	c.s.m.	C.F. PER S.M.	C.F. PER S.M.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
July 7	12 Mid't	0.26	0.26	0			0	July 8	5 pm	27.25	70.30	43.05			1,704,328
					2.10	7560							43.23	77,814	
July 8	1 am	0.30	4.50	4.20			7560		5:30 pm	28.90	72.30	43.40			1,782,142
					6.20	22,320							40.18	72,324	
	2 am	0.40	8.60	8.20			29,880		6 pm	30.30	67.25	36.95			1,854,466
					10.15	36,540							30.38	109,368	
	3 am	0.50	12.60	12.10			66,420		7 pm	32.40	56.20	23.80			1,963,834
					14.12	50,832							17.75	63,900	
	4 am	0.75	16.90	16.15			117,252		8 pm	33.60	45.30	11.70			2,027,734
					18.08	65,088							5.85	21,060	
	5 am	1.00	21.00	20.00			182,340		9 pm	33.80	33.80	0			2,048,794
					21.85	78,660							-5.43	-19,548	
	6 am	1.50	25.20	23.70			261,000		10 pm	33.60	22.75	-10.85			2,029,246
					25.50	91,800							-15.80	-56,880	
	7 am	2.00	29.30	27.30			352,800		11 pm	32.50	11.75	-20.75			1,972,366
					28.80	103,680							-25.82	-92,952	
	8 am	3.00	33.30	30.30			456,480		12 Mid't	30.90	0	-30.90			1,879,414
					31.80	114,480		RECESSION SIDE							
	9 am	4.20	37.50	33.30			570,960	July 14	Noon	0	0	0			0
					34.55	124,380							0.33	42,768	
	10 am	5.80	41.60	35.80			695,340	" 12	Mid't	0.65	0	0.65			42,768
					36.80	132,480							1.08	93,312	
	11 am	8.00	45.80	37.80			827,820	" 11	"	1.50	0	1.50			136,080
					38.45	138,420							2.10	181,440	
	12 Noon	10.90	50.00	39.10			966,240	" 10	"	2.70	0	2.70			317,520
					39.45	140,020							4.15	358,560	
	1 pm	14.20	58.00	39.80			1,106,260	" 9	"	5.60	0	5.60			676,080
					40.25	144,900							9.00	388,800	
	2 pm	17.50	58.20	40.70			1,251,160		Noon	12.40	0	12.40			1,064,880
					41.10	147,960							16.10	347,760	
	3 pm	20.75	62.25	41.50			1,399,120		6 am	19.80	0	19.80			1,412,640
					42.00	151,200							22.35	241,380	
	4 pm	24.00	66.50	42.50			1,550,320		9 am	24.90	0	24.90			1,654,020
					42.78	154,008							27.90	268,920	
	5 pm	27.25	70.30	43.05			1,704,328		12 Mid't	30.90	0	30.90			1,922,940

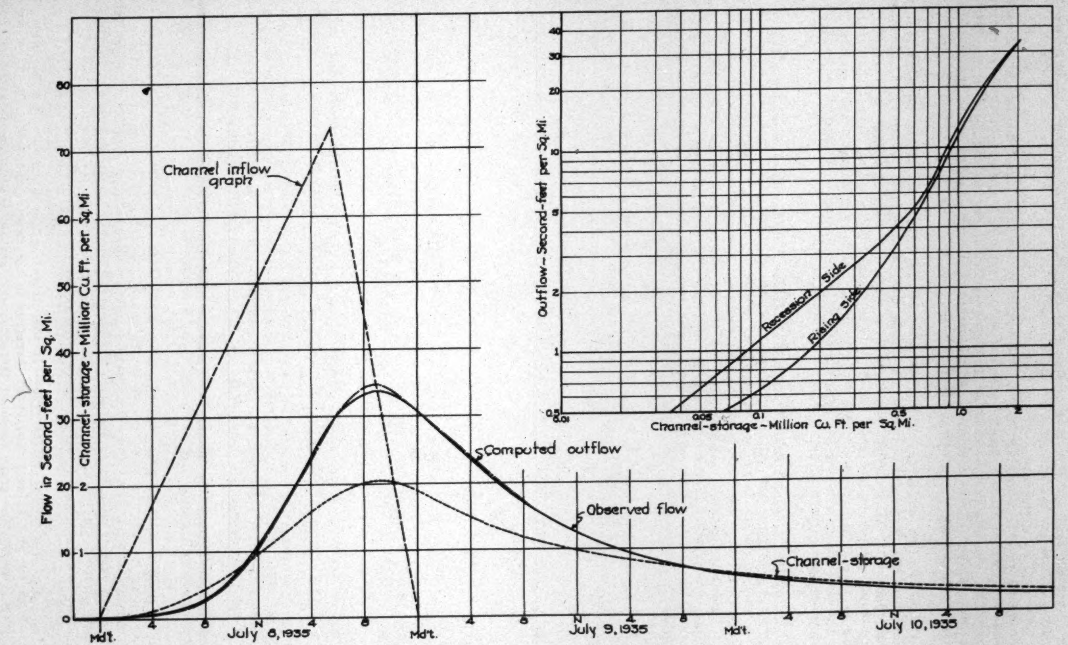


FIG. 4 ~ TIOGA RIVER NEAR ERWINS, N.Y. ~ DRAINAGE-AREA, 1370 SQ. MI.

Table 1, and opposite each is placed the outflow-rate [column (3)] and the inflow-rate [column (4)] derived from the hydrograph. The difference [column (5)] is the rate of increase of channel-storage at the given time, and the mean of these rates at the beginning and end of the time-interval [column (6)] multiplied by the time-increment (in this case 3,600 seconds) gives the increment of channel-storage for the given time-interval. By summation of these increments [column (8)], the total channel-storage for any given time from the beginning of the rise to the crest is obtained. For recession-stages the method of direct summation under the recession-graph is used, as described in a previous paper [1].

The dotted line on Figure 4 shows the march of channel-storage during the stream-rise and the insert on Figure 4 shows the channel-storage outflow-rate relation-curves for rising and receding stages. It will be noted that there is a hysteresis loop of channel-storage, the channel-storage being greater, at the same stage, for rising than for receding stages, and attaining a maximum at the outflow-crest. In the vicinity of the outflow-crest the channel-storage is sensibly the same for both rising and receding stages. Other examples of channel-storage curves are shown on subsequent figures.

Construction of channel-outflow graph from virtual channel-inflow graph and channel-storage outflow-rate relations--The following method of numerical solution of this problem applies to all forms of channel-inflow graphs and all types of channel-storage-outflow relations and to cases where the relation of channel-storage to outflow is not the same for rising as for receding stages. Subdividing the inflow-graph into equal time-intervals t and using subscripts 1 and 2 to designate conditions at the beginning and end of given time-increments, and letting I, q, and S represent inflow- and outflow-rates and channel-storage, respectively, then the storage-equation gives

$$(I_1 + I_2)t/2 = (q_1 + q_2)t/2 + (S_2 - S_1) \tag{8}$$

Let $(I_1 + I_2)/2 = I_a$.

$$I_a t = (q_1 + q_2)t/2 + (S_2 - S_1) \tag{9}$$

S_1 is known and

$$S_2 = K_{cs} q_2^{1/M} \tag{10}$$

Let

$$2I_a t - q_1 t + 2S_1 = q_2 t + 2K_{cs} q_2^{1/M} = \varphi(q_2) \tag{11}$$

Compute the values of $\varphi(q_2)$ for

$$\varphi(q_2) = q_2 t + 2K_{cs} q_2^{1/M} \tag{12}$$

for a series of assumed values of q_2. Computations of $\varphi(q_2)$ are carried out as shown on Table 2. The resulting $\varphi(q_2)$-curves for rising and receding stages are given on Figure 5. To compute a point on the hydrograph, call the right-hand member of equation (12) Z and compute its value for the given time-interval. Then find on the $\varphi(q_2)$-curve the value of q_2 which makes $Z = \varphi(q_2)$. This is the value of the channel-outflow at the end of the given time-interval and the beginning of the next succeeding time-interval. From the channel-storage curve take off the corresponding value of S_2. This becomes the value of S_1 for the next succeeding time-interval.

The computed channel-outflow graph is shown on Figure 4. The computations of this graph are carried out as shown on Table 3.

It is to be noted that $(S_2 - S_1)$ becomes negative after the outflow-crest is passed. When the computation has been carried through to the end of channel-inflow it can be continued to the end of channel-outflow, using the appropriate channel-storage-outflow relation. Longer time-intervals can usually be used in computing the recession-curve and new diagrams of channel-storage $\varphi(q_2)$ should be prepared. During the net recession-period following P_2, the inflow is zero and the computation of Z is simplified. The values of $\varphi(q_2)$ remain the same as before.

Validity of the virtual-inflow graph--If the virtual-inflow graph is correctly drawn, the outflow-graph can be precisely duplicated therefrom in the manner described. If it is not correctly drawn, the outflow-graph computed therefrom will not agree with the observed outflow-graph. This is illustrated by Figure 6, which shows by a solid line the observed outflow-graph of the Fall Creek flood at Ithaca, New York, July, 1935. The inflow-graph correctly derived in the manner above described is shown by the triangle ABD, and the outflow-graph computed therefrom is in close agreement with the observed outflow-graph. The triangle ACE is an incorrect V-I graph with too long a time-base and too low a crest, and it will be noted that the outflow-graph computed therefrom does not conform closely to the observed outflow-graph.

It should be noted that the computation of an outflow-graph from a V-I graph is not a mere reversal of the process by which the inflow-graph is derived. It involves certain relations of channel-storage which are not a priori necessarily involved in the derivation of the V-I graph. At the crest-stage the channel-storage is at or near its maximum value and this represents the total accumulation of channel-storage during rising stages. It also represents the total depletion of channel-storage which must take place during recession, and these two quantities must be equal. If the V-I graph is correctly determined, these two quantities will balance and the computed outflow-graph will conform to the observed outflow-graph. If the V-I graph is not correctly determined, it will in general lead to a computed outflow-graph in which the channel-storage for rising and receding stages does not balance, and the computed graph will depart from the observed graph, particularly near the crest and during recession. There is therefore another requirement for a correct channel-inflow graph in addition to the four used in constructing the V-I graph, namely, it must balance the channel-storage for rising and receding stages.

Channel-storage, after surface-runoff ends, is determined by and only by the form of the outflow-graph and is independent of the assumed inflow-graph, whereas for rising stages, the channel storage-stage relation depends both on the assumed inflow-graph and the observed outflow-graph. Now, since (channel-storage + outflow) = inflow, it follows that with an error in the inflow-graph there is an error in the channel storage-stage relation for rising stages, with the result that the storage-equation cannot balance for the recession-side of the outflow-graph, using the channel storage-stage outflow-relation derived therefrom. In other words, the areas under the inflow- and outflow-graphs can be equal if and only if the channel storage-outflow relations are correct, both for rising and receding stages, and they will be correct for rising stages only if the assumed inflow-graph is the true channel-inflow graph.

TABLE 2 - COMPUTATION OF ϕq-CURVE
TIOGA RIVER NEAR ERWINS, N.Y.
RISE OF JULY 8, 1935

q_1 C.S.M.	$q_1 t$ (t=3600 Secs.)	$\frac{S}{t}$ C.F. per S.M.	ϕq_1 =(2)−2(3)
(1)	(2)	(3)	(4)
Rising Side			
1	3,600	180,000	363,600
2	7,200	340,000	687,200
4	14,400	550,000	1,114,400
6	21,600	700,000	1,421,600
8	28,800	825,000	1,678,800
10	36,000	930,000	1,896,000
15	54,000	1,160,000	2,374,000
20	72,000	1,390,000	2,852,000
25	90,000	1,610,000	3,310,000
30	108,000	1,850,000	3,808,000
35	126,000	2,080,000	4,286,000
40	144,000	2,310,000	4,764,000
Recession Side			
1	3,600	87,000	177,600
2	7,200	210,000	427,200
4	14,400	475,000	964,400
6	21,600	675,000	1,371,600
8	28,800	790,000	1,608,800
10	36,000	870,000	1,776,000
15	54,000	1,100,000	2,254,000
20	72,000	1,320,000	2,712,000
25	90,000	1,560,000	3,210,000
30	108,000	1,820,000	3,748,000

Uses of virtual channel-inflow graphs--The many practical applications of V-I graphs will not be discussed in detail but include the following:

(1) Determination of true time of transit--There has been much confusion regarding time of transit of surface-runoff and channel-flow, or difference of time of occurrence of maximum rain-intensity and maximum channel-outflow. This interval is made up of three components: (a) Channel-inflow lag, or difference of time of occurrence of maximum rain-intensity and maximum channel-inflow. This lag-interval is due to the reservoir-effect of surface-detention. (b) Time of channel-transit or difference of time of occurrence of maximum channel-inflow and maximum channel-storage at the outlet. This is chiefly the actual time of transit of water in the channel, either by hydraulic or wave-flow, but modified by the sequence of inflow. (c) Channel-storage reservoir-lag--This is true reservoir-lag due to channel-storage and is the difference of time of occurrence of the crest of the V-I graph and the crest of the channel-outflow graph. Hitherto it has not been possible to segregate these components. The use of the V-I graph makes their separation possible.

(2) Law of overland-flow--The law of overland-flow can readily be determined for a simple sub-area tributary to one side of the reach of a stream if the surface-runoff is measured as in case of a runoff-plat experiment. The determination of the corresponding law of overland-flow for a larger drainage-basin made up of a large number of individual sub-areas, with different slopes and lengths of overland-flow, can be accomplished if the actual channel-inflow graph is given, together with the areal rainfall-excess graph. It is possible to construct the areal rainfall-excess graph for a given drainage-basin from rainfall- and infiltration-data if sufficiently complete, and since

the rainfall-excess if sensibly equal to the surface-runoff, this gives the runoff-volume. The two graphs together make it possible to determine (1) the amount of surface-detention, (2) law of overland-flow, (3) lag-interval due to surface-detention, or the interval between maximum rain-intensity and maximum channel-inflow.

(3) Flood-routing--Since the channel-outflow graph represents the channel-inflow graph as modified by channel-storage, a virtual-inflow graph provides a simple means of flood-routing in such a manner as to take into account changes in inflow-conditions. If, for example, virtual-inflow graphs have been determined for existing conditions, together with the corresponding channel-storage graphs, then for a flood produced under modified conditions, the corrected channel-inflow graphs can be obtained for different points on the drainage-basin and these, in conjunction with the channel-storage relations, provide a ready means for determining the corresponding channel-outflow graphs.

(4) Construction of synthetic unit-graphs--The virtual channel-inflow graph provides a simple, direct means of constructing accurately the channel-outflow graph corresponding to a unit-storm of any duration and intensity. The resulting graph may be used as a unit-graph or distribution-graph for determining outflow-graphs in storms of other intensities. Unit-graphs can be derived in this way for any given amount of channel-storage and any given amount of initial inflow or ground-water flow.

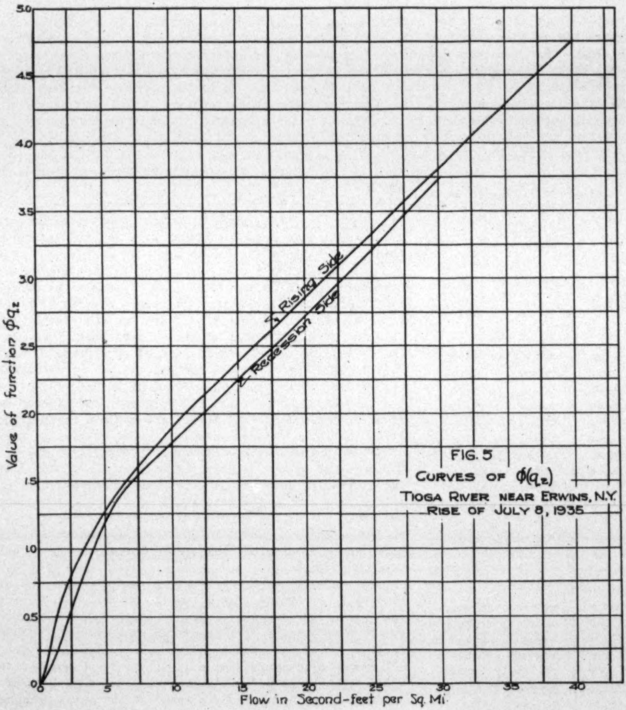


FIG. 5

CURVES OF $\phi(q_z)$

TIOGA RIVER NEAR ERWINS, N.Y.
RISE OF JULY 8, 1935

References

[1] Robert E. Horton, Natural stream-channel storage, Trans. Amer. Geophys. Union, pp. 406-432, 1936.

[2] Robert E. Horton, Natural stream-channel storage (second paper), Trans. Amer. Geophys. Union, pp. 440-456, 1937.

[3] Robert E. Horton, Informal notes on the structure of the hydrograph and the relation between the channel outflow and channel inflow graphs; (processed); lecture given at Coshocton, Ohio, Experiment Station of the Soil Conservation Service, September, 1937. (The principles governing the construction of V-I graphs were first outlined in this paper.)

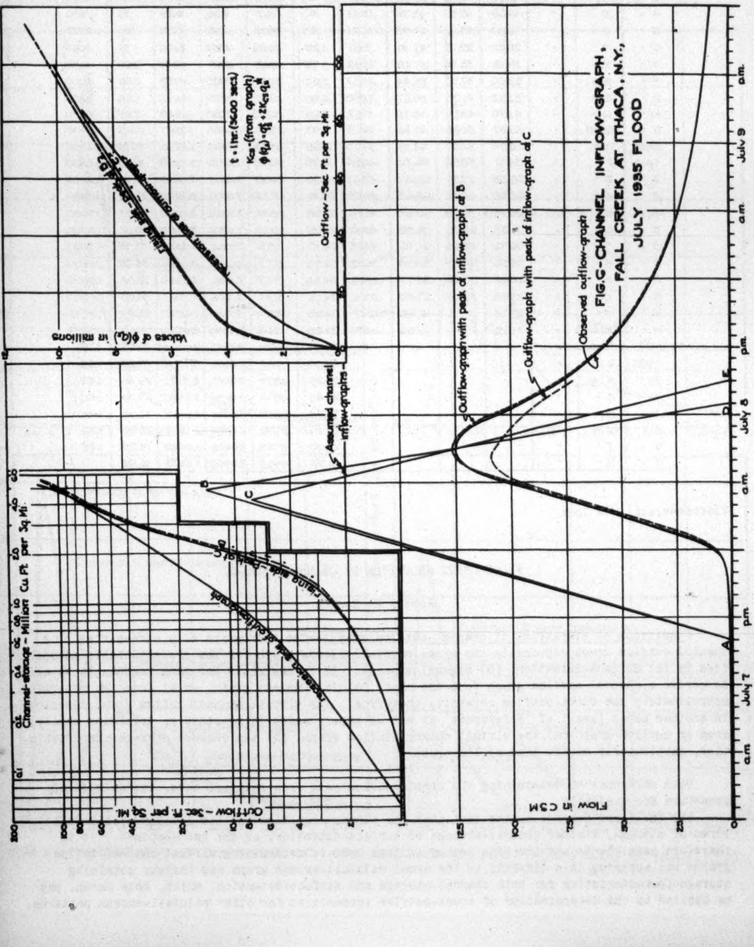


FIG. G-CHANNEL INFLOW-GRAPH, FALL CREEK AT ITHACA, N.Y., JULY 1935 FLOOD

TABLE 5 - COMPUTATION OF CHANNEL-OUTFLOW GRAPH - TIOGA RIVER NEAR ERWINS, N.Y.
RISE OF JULY 8, 1935

t_1	t_2	$2t$ Seconds	I_1 c.s.m.	I_2 c.s.m.	I_{av} c.s.m.	$2t\,I_{av.}$ (Millions)	q_1 c.s.m.	q_1t	$2S_1$ (Millions) C.F. per S.M.	Z (10)+(5)-(9)	q_2 c.s.m.	S_2 (Millions) C.F. per S.M.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Md't.	1a.m.	7200	0	4.17	2.08	0,0150	0.27	.0010	.0200	.0340	0.28	0.0100
1a.m.	2 "	"	4.17	8.34	6.25	.0450	.28	.0011	.0200	.0639	.30	.0100
2 "	3 "	"	8.34	12.51	10.42	.0750	.30	.0011	.0200	.0939	.40	.0320
3 "	4 "	"	12.51	16.68	14.59	.1050	.40	.0014	.0640	.1676	.60	.0900
4 "	5 "	"	16.68	20.85	18.76	.1351	.60	.0022	.1800	.3129	.90	.1580
5 "	6 "	"	20.85	25.02	22.93	.1651	.90	.0032	.3160	.4779	1.25	.2250
6 "	7 "	"	25.02	29.19	27.10	.1951	1.25	.0045	.4500	.6406	1.75	.3080
7 "	8 "	"	29.19	33.36	31.28	.2252	1.75	.0063	.6160	.8349	2.60	.4150
8 "	9 "	"	33.36	37.53	35.44	.2552	2.60	.0094	.8300	1.0758	3.80	.5400
9 "	10 "	"	37.53	41.70	39.62	.2853	3.80	.0137	1.0800	1.3516	5.65	.6800
10 "	11 "	"	41.70	45.87	43.78	.3152	5.65	.0203	1.3600	1.6549	7.95	.8200
11 "	noon	"	45.87	50.04	47.96	.3453	7.95	.0286	1.6400	1.9567	10.65	.9600
noon	1p.m.	"	50.04	54.21	52.13	.3753	10.65	.0383	1.9200	2.2570	13.75	1.1000
1p.m.	2 "	"	54.21	58.38	56.30	.4054	13.75	.0495	2.2000	2.5559	16.80	1.2400
2 "	3 "	"	58.38	62.55	60.47	.4347	16.80	.0605	2.4800	2.8542	20.10	1.4000
3 "	4 "	"	62.55	66.72	64.63	.4653	20.10	.0724	2.8000	3.1929	23.50	1.5500
4 "	5 "	"	66.72	70.35	68.55	.4934	23.50	.0846	3.1000	3.5088	26.75	1.7000
5 "	6 "	"	70.35	66.72	70.08	.5046	26.75	.0963	3.4000	3.8083	30.10	1.8500
6 "	7 "	"	66.72	55.60	61.16	.4403	30.10	.1083	3.7000	4.0320	32.75	2.0000
7 "	8 "	"	55.60	44.48	50.04	.3603	32.75	.1179	4.0000	4.2424	34.60	2.0500
8 "	9 "	"	44.48	33.36	38.92	.2802	34.60	.1245	4.1000	4.2557	34.75	2.0600
9 "	10 "	"	33.36	22.24	27.80	.2002	34.75	.1251	4.1200	4.1951	34.00	2.0300
10 "	11 "	"	22.24	11.12	16.68	.1201	34.00	.1224	4.0600	4.0577	32.60	1.9700
11 "	md't.	"	11.12	0	5.56	.0400	32.60	.1174	3.9400	3.8626	30.60	1.8700
md't.	1a.m.	"	0	0	0	0	30.60	.1102	3.7400	3.6298	29.00	1.78
1a.m.	2 "	"					29.00	.1044	3.5600	3.4556	27.20	1.68
2 "	3 "	"					27.20	.0979	3.3600	3.2621	25.40	1.59
3 "	4 "	"					25.40	.0914	3.1800	3.0886	23.70	1.50
4 "	5 "	"					23.70	.0853	3.0000	2.9147	22.00	1.40
5 "	6 "	"					22.00	.0792	2.8000	2.7208	20.00	1.32
6 "	7 "	"					20.00	.0720	2.6400	2.5680	19.35	1.25
7 "	8 "	"					18.35	.0661	2.5000	2.4339	16.95	

Voorheesville, New York

FLOOD-CREST REDUCTION BY CHANNEL-STORAGE

Robert E. Horton

Conditions of similarity of channel-outflow graphs--The hydrograph of a stream-rise or a channel-outflow graph represents the areal rainfall-excess graph for the drainage-basin as modified by (a) surface-detention, (b) channel-storage. It is desirable for many reasons to be able to derive a channel-outflow graph from the areal rainfall-excess graph, or at least to determine approximately the crest-outflow intensity therefrom. The virtual channel-inflow graph described in another paper [see 1 of "References" at end of paper] makes it possible to determine easily from an outflow-graph (a) the virtual channel-inflow graph, (b) the channel-storage characteristics, particularly at the time of the crest.

With reference to determining the crest-outflow rate from rainfall-data, two methods of procedure are available:

(1) The first depends on the fact that the storage-equation applies equally well to all forms of storage, whether channel-storage or surface-detention, or the two combined. It is therefore possible to use the same method as that used in determining virtual channel-inflow graphs but applying this directly to the areal rainfall-excess graph and thereby obtaining storage-characteristics for both channel-storage and surface-detention, which, once known, may be applied to the determination of crest-outflow intensities for other rainfall-excess patterns.

(2) From the V-I graph and the rainfall-excess graph, to determine the surface-detention effect separately. Then apply this to the areal rainfall-excess graph to derive a channel-inflow graph, and from the latter derive the channel-outflow graph, or at least the reduction in crest-intensity.

The latter method has the advantage that the operation of surface-detention storage and channel-storage may not be identical in two different storms. Consequently the relationships between areal rainfall-excess graphs and channel-outflow graphs are not likely to be as uniform or consistent as the relationships between V-I graphs and channel-outflow graphs. The present paper is devoted entirely to the latter relationships.

It is obvious from the storage-equation that for the same rainfall-excess pattern on two adjacent drainage-basins or at two different gaging-stations on the same drainage-basin, the channel-outflow graphs will be closely similar if and only if the channel-storage characteristics are similar. Likewise, outflow-graphs for the same stream and station will be similar if the

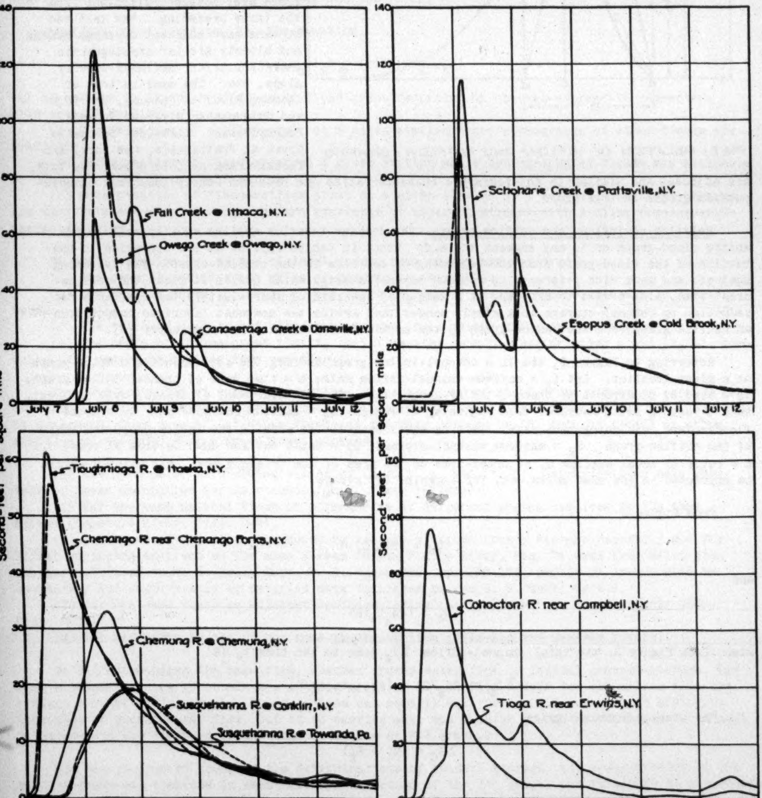


FIG. 1 -HYDROGRAPHS OF DISCHARGE OF VARIOUS STREAMS, N.Y. STATE FLOOD OF JULY, 1935

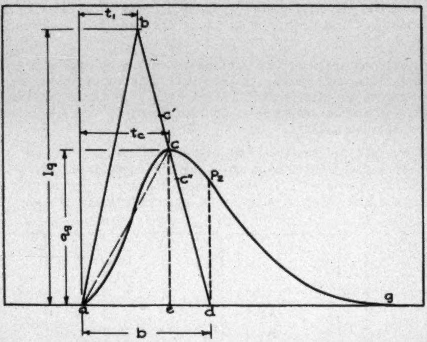


FIG.2 – RELATION OF INFLOW- AND OUTFLOW - GRAPHS

channel-inflow graphs are similar. Illustrations of the close similarity of channel-outflow graphs on adjacent drainage-basins with similar rainfall-excess patterns and similar channel-storage characteristics are afforded by the flood of July, 1935, in central New York. Figure 1 shows the outflow-graphs on different streams. There is a close similarity in the outflow-graphs for Fall Creek, Owego Creek, and Canaseraga Creek; also for Tioughnioga River and Chenango River. These are, however, different from the three preceding. The last two streams have adjacent drainage-basins and closely similar physiographic characteristics, drainage-density, slope, etc. The same is true of Chemung River at Chemung, New York and Susquehanna River at Towanda, Pennsylvania. Likewise, Schoharie Creek at Prattsville, New York, and Esopus Creek at Cold Brook, New York, are adjacent and similar in physiographic characteristics and produced nearly identical channel-outflow graphs in this flood.

Relation of inflow- and outflow-crests--The storage-equation applies equally well to an entire flood-graph or to any segment thereof. Hence it can be applied at one operation to the portion of the flood-graph from the beginning of the rise to the outflow-crest. The following analysis was made with reference to maximum channel-storage which occurs at about the outflow-crest time, with a view to arriving at a method of determining approximately the outflow-crest reduction by channel-storage in a simple manner that avoids the somewhat laborious computation of an outflow-graph from the inflow-graph by the method described in a previous paper [1].

Referring to Figure 2, abd is a channel-inflow graph and acg the corresponding outflow-graph at a given location. Let I_g = maximum channel-inflow rate; b = time base of channel-inflow graph; t_1 = time of occurrence of channel-inflow crest; t_c = time of occurrence of channel-outflow crest, both t_1 and t_c being measured from beginning of runoff; q_g = maximum outflow-rate; Q_s = total flood-volume, excluding base-flow. This is equal both to the area of the inflow-graph and that of the outflow-graph. S_g = maximum channel-storage; Q_c = total outflow down to time of crest t_c; c = ratio of total outflow Q_c at crest-time to the area of the triangle ace. All volumes should be expressed in the same units, as, for example, c.f.s-days.

From Figure 2

$$Q_s = (bI_g/2)$$

and

$$Q_c = (cq_gt_c/2)$$

Also, from Figure 2, the total channel-inflow ΣI_g down to the time t_c is

$$\Sigma I_g = (bI_g/2) - [(b - t_c)q_g/2]$$

The storage equation gives

$$\Sigma I_g = (Q_c + S_g)$$

or

$$(bI_g/2) - (bq_g/2) + (t_cq_g/2) = [(ct_cq_g/2) + S_g]$$

$$(bI_g/2) = (bq_g/2) - [(1 - c)\ t_c q_g/2] + S_g$$

$$(q_g/I_g) - [(1 - c)\ t_c/b](q_g/I_g) + (S_g/Q_s) = 1$$

Hence

$$[1 - (1 - c)\ t_c/b](q_g/I_g) + (S_g/Q_s) = 1$$

Let $(1/\rho) = [1 - (1 - c)\ t_c/b]$, then (1)

$$(q_g/I_g) = [\rho(1 - S_g/Q_s)] \quad (2)$$

This equation makes it possible to determine the outflow-crest where the inflow-graph is known, together with the maximum channel-storage and the factor ρ.

Application of equation (2)--The equation

$$(q_g/I_g) = [\rho(1 - S_g/Q_s)] \quad (2)$$

may be applied to the determination of flood-crest reduction by channel-storage in connection with several problems:

(1) Determination of outflow-crest at a given station where hydrographs of other floods are available.

(2) Determination of flood-crest at a given station where hydrographs of floods are available at other stations on the same stream.

(3) Determination of flood-outflow crest at a given station on a stream on which no gagings are available but flood-hydrographs are available on adjacent streams with similar physiographic characteristics.

To apply equation (2) to any of these cases, four things are required:

(1) The channel-inflow graph which is assumed is available.

(2) The maximum channel-storage or the ratio (S_g/Q_s) of maximum channel-storage to total surface-runoff.

(3) The ratio of c of runoff antecedent to the crest to the triangle ace (Fig. 2).

(4) The ratio of inflow-crest time t_c to inflow-time base b. Having given c and (t_c/b), the value of ρ can be determined from equation (1)

The practicability of applying equation (2) to problems of flood-crest reduction depends on the accuracy with which the values of these quantities applicable to a given stream and flood can be determined from data of (a) other floods at the same station or (b) data of floods at other stations on the same stream or adjacent streams.

For the purpose of determining values of (S_g/Q_s), c, and (t_c/b), determinations have been made of these quantities for four conditions. These include:

(1) For the same natural flood or stream-rise at different gaging-stations on the same stream (Delaware River, Figs. 3-6).

(2) For an artificial flood produced by release of water from a storage-reservoir and for different gaging-stations on the same stream (North Platte River, Fig. 7; data from daily discharges published in U. S. Geol. Surv. W.-S. Paper 786, pp. 168-179, partly as interpreted by the author and supplemented by detailed data furnished by the U. S. Geol. Surv.).

(3) For the same flood on adjacent drainage-basins (central New York flood of July 1935, Figs. 8-12).

(4) For different floods at the same gaging-station (Delaware and Genesee rivers).

In all these cases the base-flow, whether ground-water flow or initial channel-storage, has been eliminated so as to obtain the outflow-graph or net surface-runoff for comparison with the virtual channel-inflow graph. (Computations can equally well be carried out without deducting base-flow or ground-water flow, but if so carried out, the base or ground-water flow or both must be determined and included in the channel-inflow or V-I graph.)

For the purpose of checking the determinations of channel-storage, the crest-portion of the outflow-graph was computed in each case by the method of the V-I graph, and reference to Figures 3 to 12 shows substantial agreement between the observed and computed outflow-crests.

Data were tabulated for all the cases for which computations were made, as shown on Table 1. Column (2) shows the ratio of the maximum channel-storage at or near the crest, to the total surface-runoff. It is interesting to note that in case of all of these floods, 48 to 75 per cent of the total flood-volume, and sometimes more, remained in the stream-system as channel-storage at the time of the outflow-crest. Column (3) of the Table shows the ratio of the outflow-crest to the channel-inflow crest. This quantity subtracted from unity represents the fraction of crest-reduction by channel-storage.

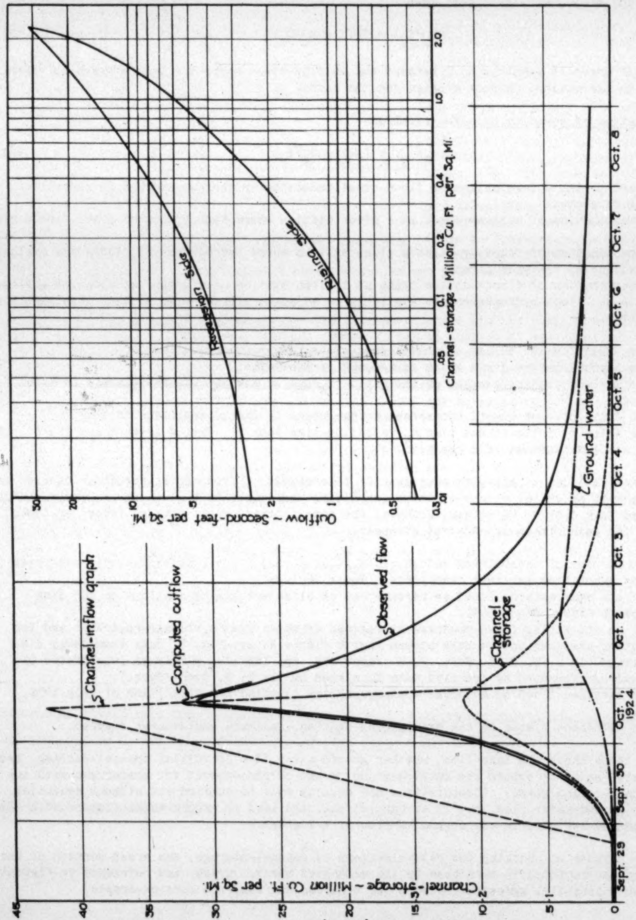


FIG. 3-DELAWARE RIVER AT PORT JERVIS, N.Y.-DRAINAGE-AREA, 3076 SQ. MI.

In the examples given on Table 1 the flood-crest reduction ranged from less than 30 per cent to more than 80 per cent.

The ratio (S_g/Q_s)--The maximum channel-storage is easily determined from inflow- and outflow-graphs, since it is the area between these graphs from the beginning of the rise to the outflow-crest. The data given on Table 1 show that the ratio (S_g/Q_s) is relatively constant, its usual value being between 50 and 70 per cent. This ratio varies, however, directly with the ratio of outflow-crest to flood-volume, and determinations of these two ratios for different floods will supply data useful as a guide in selecting appropriate values of the ratio for ap-

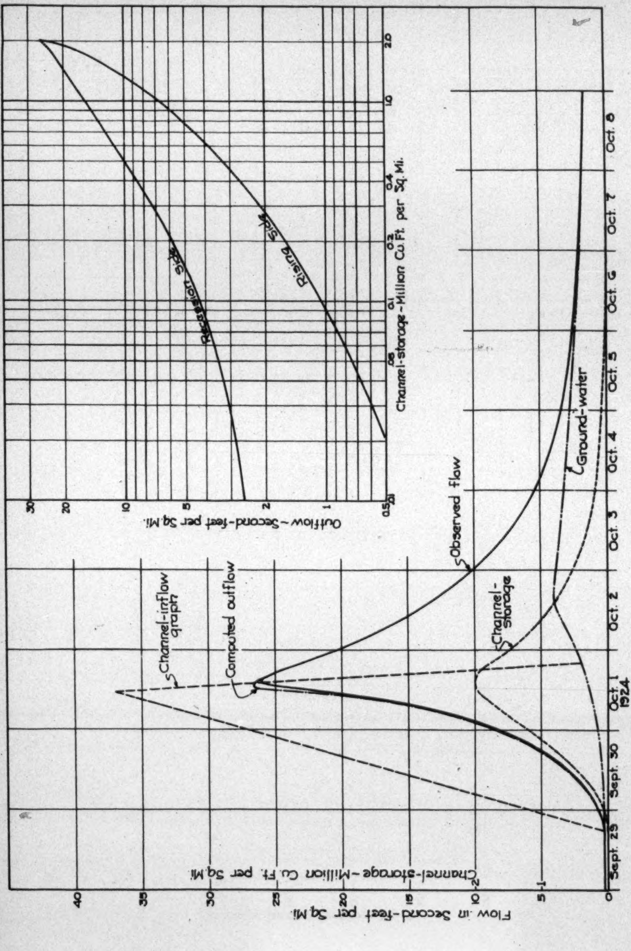


FIG.4-DELAWARE RIVER AT BELVIDERE, N.J.-DRAINAGE-AREA, 4542 SQ. MI.

plication to other cases. In some instances the value of this ratio is much higher than 70 per cent, as, for example, in case of the floods of the Tioughnioga and Chenango rivers listed. These floods on adjacent streams were, as shown by Figure 1, closely similar and have similar values of the maximum storage-ratio. In case of Fall Creek and Owego Creek, with flood-graphs of similar form, as shown on Figure 1, there are large differences in the values of the (S_s/Q_s)-ratio. This is, however, due to the fact that while the graphs are of similar form, the flood was double-crested and the secondary crest, and consequently the value of Q_s, was much higher on Fall Creek than on Owego Creek. With reference to the flood on North Platte River, the (S_s/Q_s)-ratio is nearly constant. For the flood of the Delaware River on October 1, 1924, this ratio is

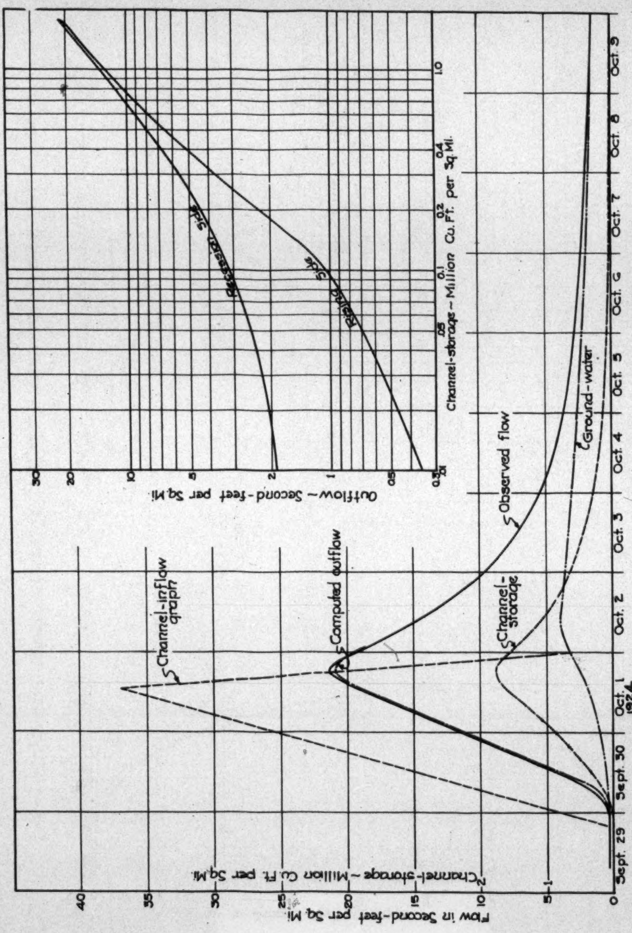


FIG.5-DELAWARE RIVER AT RIEGELSVILLE, N.J.-DRAINAGE-AREA, 6344 SQ.MI.

practically identical for Port Jervis and Belvidere; also identical, but lower, for Riegelsville and Trenton. The last-named stations are below the mouth of Lehigh River and the channel-storage characteristics are similar for the two upstream stations and for the two downstream stations but dissimilar as between the upstream and downstream stations.

If two stations, one for comparison, the other for determination of flood-crest reduction, are both on the same stream, then a portion of the channel-storage is common to both stations and the value of the ratio (S_g/Q_s) will usually be nearly the same unless, as in the case of the Delaware River, a large tributary enters between the stations. The data indicate that a fairly close determination of the ratio (S_g/Q_s) can be made for a given flood at a given location from data of other floods at the same station or of the same flood at adjacent stations.

At or near a flood-crest the stream-slope is normal, that is, parallel to the stream-channel, and the channel-storage is sensibly the same in the vicinity of the crest for rising and receding

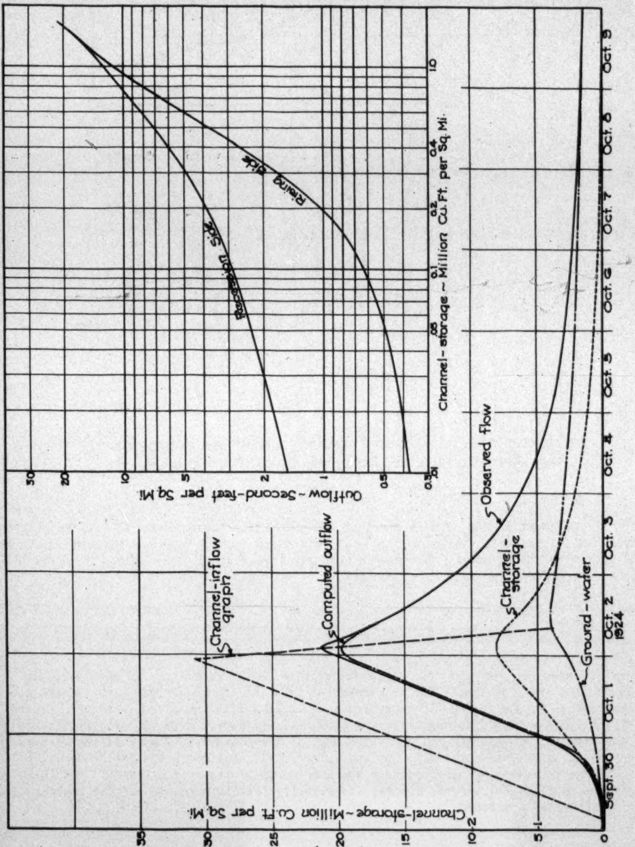


FIG. 6 - DELAWARE RIVER AT TRENTON, N.J. ~ DRAINAGE-AREA, 6796 SQ. MI.

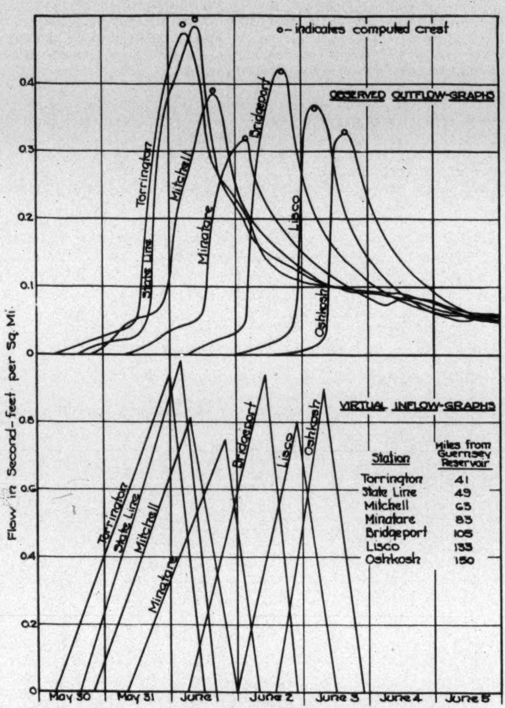


FIG. 7 - VIRTUAL INFLOW- AND OBSERVED OUTFLOW-GRAPHS FOR FLOW RELEASE FROM GUERNSEY RESERVOIR, NORTH PLATTE RIVER - MAY 31, 1935

stages. If the maximum channel-storage has been determined for lower floods at a given station, these values can be platted in terms of flood-volume and the line through the platted points can be used to determine approximately the maximum channel-storage for a higher flood from the known flood-volume derived from the channel-inflow graph.

The ratio of (t_c/b)--Values of this ratio are given in column (5), Table 1, from which it appears that this ratio is relatively constant, ranging, in the 31 cases listed, from 0.80 to 0.95.

At first it might appear that since this ratio is so nearly constant, its average value could be used directly to determine the outflow-crest from the channel-inflow graph, since the outflow-crest occurs at a point on the recession-side of the inflow-graph corresponding to the time t_c. Actually this mode of determining the outflow-crest serves only as a rough first approximation, for the reason that the recession-side of the channel-inflow graph has usually a very steep slope, and a small variation in the value of t_c, applied in the manner described, may induce a large variation in the resulting computed value of the outflow-crest. The relative constancy of the ratio (t_c/b) serves, however, to simplify the determination of the ratio ρ, in the manner subsequently described.

The factor c--This, as already described, is the ratio between the total outflow down to the time of the outflow-crest, and the triangle having as its vertices the point of beginning of runoff, the outflow-crest and a point on the base-line under the outflow-crest, as shown by column (7) of Table 1. This ratio varies in the examples given from 0.085 to 1.19, although in most cases its value lies between 0.50 and unity. The selection of the correct value of c is perhaps the most difficult factor in connection with the application of equation (2). The value of c depends on the form of the outflow-graph antecedent to the crest, which can in general be fairly closely predicted from that of the inflow-graph, and a value of c selected which has been derived from another outflow-graph of similar form.

The ratio ρ--When the values of (t_c/b) and of c are known, the value of ρ can be determined from equation (1). The values of ρ given in column (6), Table 1, were platted in terms of c, as shown on Figure 13. It will be seen that within the range in which the values of c usually oc-

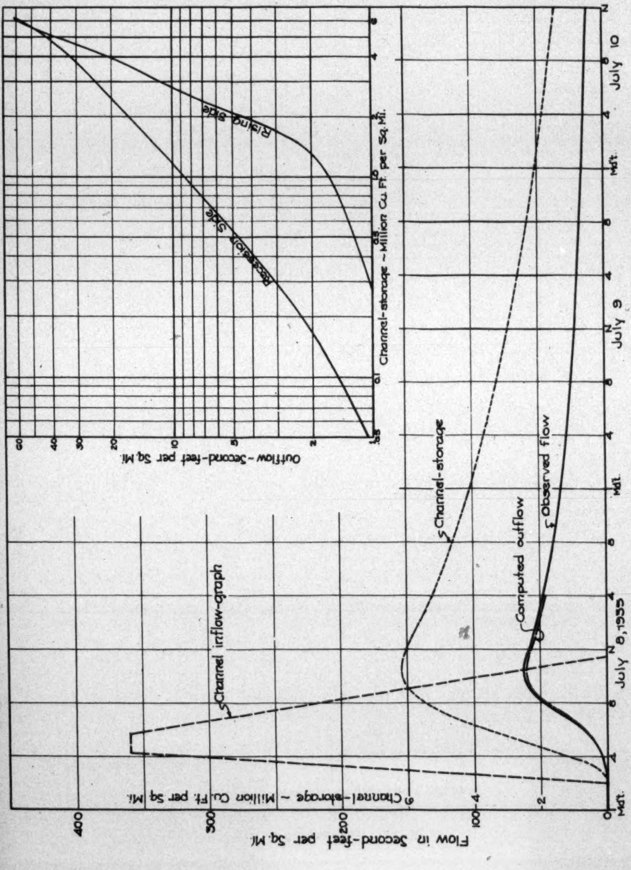


FIG. 8--TIOUGHNIOGA RIVER AT ITASKA, N.Y.--DRAINAGE-AREA, 735 SQ. MI.

cur, a variation of c produces relatively much smaller variation in the value of ρ. Hence some uncertainty in the value of c will not induce any large error in the computed outflow-crest.

Assuming the ratio (t_c/b) to be constant and with an average value 0.83, the relation of c

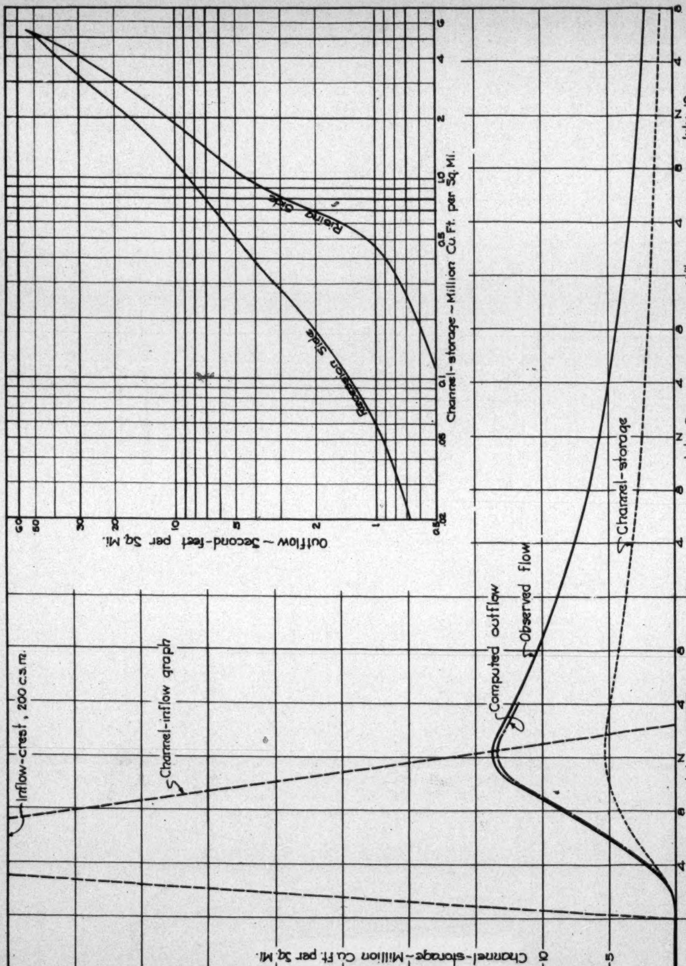


FIG.9-CHENANGO RIVER NEAR CHENANGO FORKS, N.Y.-DRAINAGE-AREA, 1492 SQ.MI.

to ρ is given by the equation

$$c = [1 - 1.20(\rho - 1)/\rho] = [(1.20/\rho) - 0.20] \qquad (3)$$

Values of ρ computed by this equation are shown by crosses on Figure 13 and it will be seen that

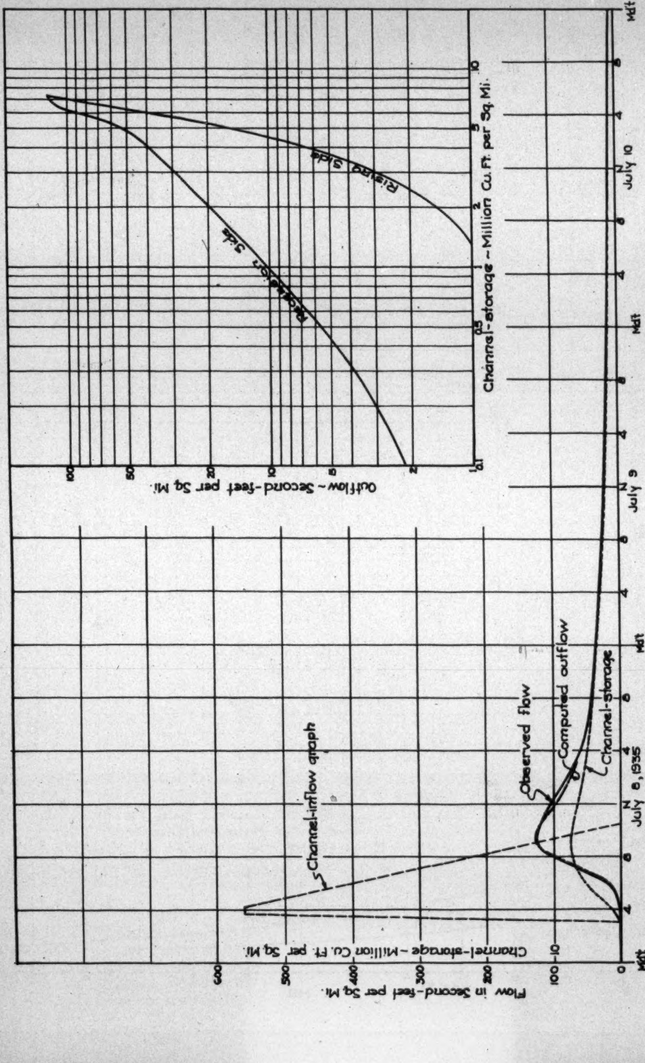


FIG. 10-OWEGO CREEK NEAR OWEGO, N.Y. -DRAINAGE-AREA, 186 SQ. MI.

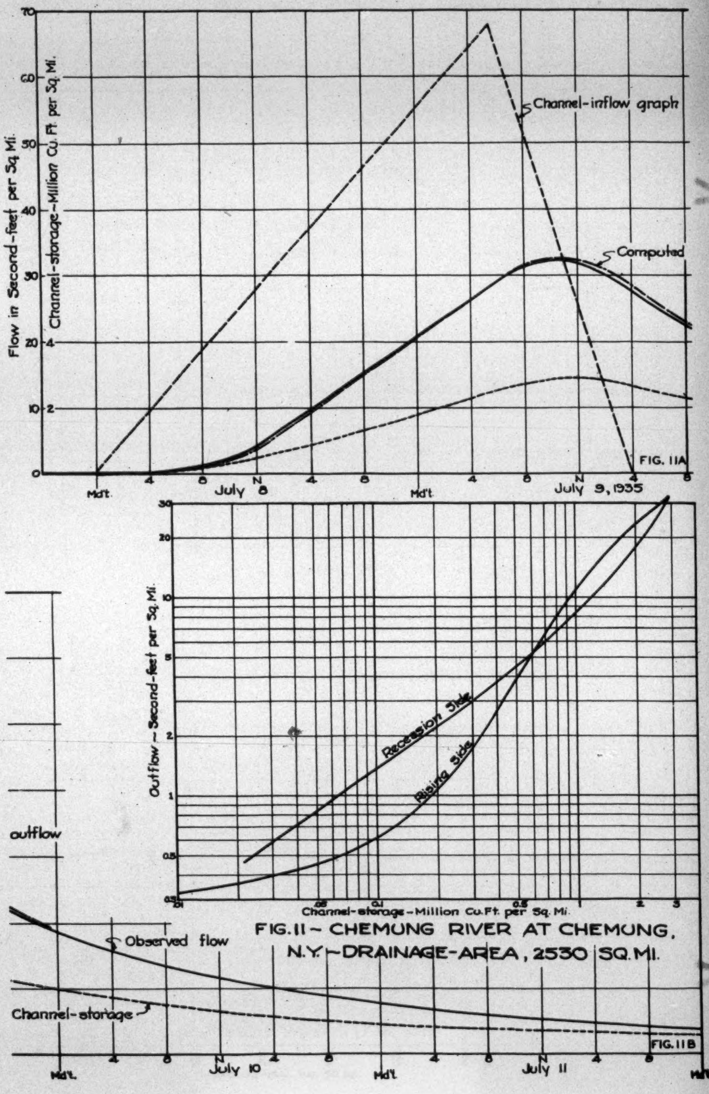
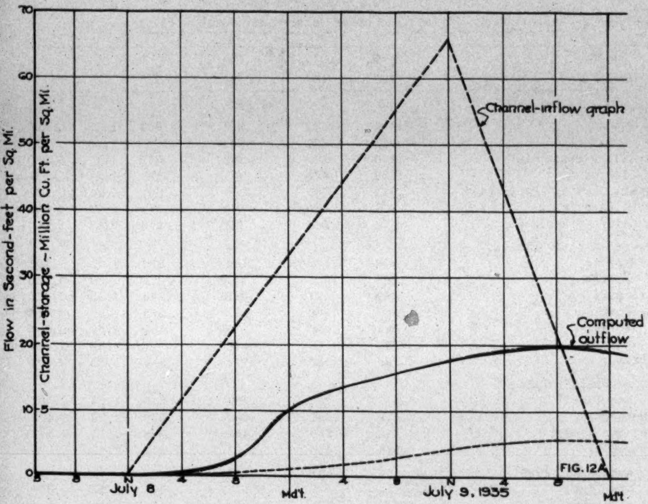


FIG. 11 - CHEMUNG RIVER AT CHEMUNG, N.Y. - DRAINAGE-AREA, 2530 SQ. MI.



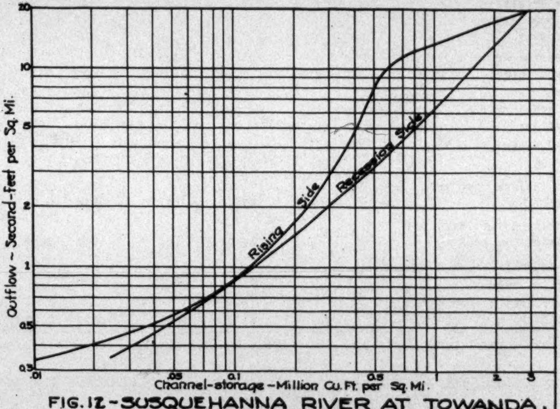


FIG. 12 – SUSQUEHANNA RIVER AT TOWANDA, PA. – DRAINAGE-AREA, 7797 SQ. MI.

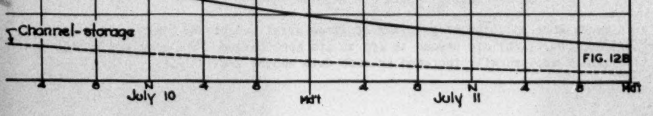


Table 1--Values of ρ, (t_c/b), and other factors for various floods

Flood (1)	(S_g/Q_s) (2)	(q_g/I_g) (3)	$1 - (S_g/Q_s)$ (4)	(t_c/b) (5)	ρ (6)	c (7)
Central New York, July 8, 1935						
Fall Creek, Ithaca	.485	.527	.515	.809	1.03	0.964
Owego Creek, Owego (1)	.902	.225	.098	.800	2.30	0.293
Tioughnioga River, Itaska (a)	.848	.170	.152	.895	1.12	0.880
Tioga River, Irwins	.655	.472	.345	.875	1.37	0.691
Chenango River, Chenango Forks (a)	.941	.280	.059	.861	4.75	0.083
Chemung River, Chemung	.598	.486	.402	.875	1.21	0.802
Susquehanna River, Towanda (b)	.672	.288	.328	.903	0.88	1.15
North Platte River, May 31, 1935						
Torrington, Wyoming	.716	.505	.284	.889	1.78	0.506
State Line, Nebraska	.663	.502	.337	.878	1.39	0.680
Mitchell, Nebraska	.658	.477	.342	.844	1.40	0.661
Minatare, Nebraska	.707	.426	.293	.895	1.45	0.653
Bridgeport, Nebraska	.681	.450	.319	.850	1.41	0.658
Lisco, Nebraska	.750	.458	.250	.805	1.83	0.436
Oshkosh, Nebraska	.788	.366	.212	.844	1.73	0.499
Delaware River, October 1, 1924						
Port Jervis, New York	.617	.722	.383	.875	1.89	0.461
Belvidere, New Jersey	.612	.694	.388	.880	1.79	0.499
Riegelsville, New Jersey	.540	.549	.460	.885	1.19	0.819
Trenton, New Jersey	.548	.643	.452	.910	1.42	0.675
Delaware River, August 25, 1933	(c)	(c)	(c)			
Port Jervis, New York				.942	1.69	0.566
Belvidere, New Jersey				.946	1.52	0.641
Riegelsville, New Jersey				.927	1.30	0.751
Trenton, New Jersey				.902	1.26	0.774
Delaware River, September 17, 1933	(c)	(c)	(c)			
Port Jervis, New York				.932	1.61	0.596
Belvidere, New Jersey				.944	1.60	0.604
Riegelsville, New Jersey				.947	1.56	0.622
Trenton, New Jersey				.910	1.27	0.767
Genesee River, St. Helena, New York, November 28, 1925	(c)	(c)	(c)	.787	1.13	0.849
Genesee River, St. Helena, New York, November 18, 1927 (b)	(c)	(c)	(c)	.918	0.850	1.191
West Branch, Delaware River, Hale Eddy, New York, November 19, 1929	(c)	(c)	(c)	.793	1.02	0.974
West Branch, Delaware River, Hale Eddy, New York, June 11, 1930	(c)	(c)	(c)	.850	1.20	0.804
Susquehanna River, Conklin, New York, October 26, 1925 (b)	(c)	(c)	(c)	.870	0.988	1.013

(a) = trapezoidal-channel inflow-graphs. (b) = broad-crested floods. (c) = values not determined.

these values are in close agreement with the observed values. Consequently equation (3) may be used without sensible error for the determination of ρ.

Conclusions--Equation (2)

$$(q_g/I_g) = \rho(1 - S_g/Q_s) \qquad (2)$$

is not offered as a ready-made solution of problems of flood-crest reduction. Many more determinations of (S_g/Q_s), c, and (t_c/b) are needed to aid in its application. The accuracy with which this equation can be applied will increase as such data become available.

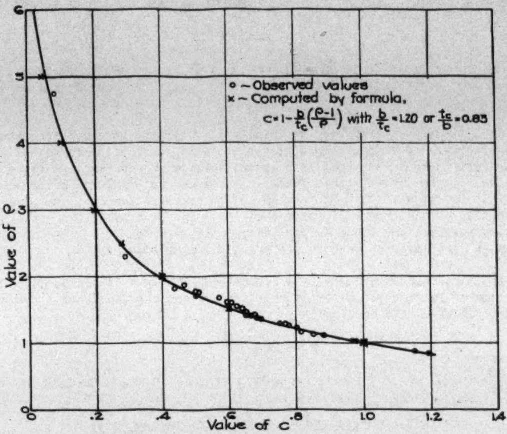


FIG.13 ~ RELATION OF OBSERVED AND COMPUTED VALUES OF c AND ρ

Some factors determined by judgment must always be used in determining flood-crest reduction where no gagings are available, whatever method is applied. The method here given is simple and separates the factors involving judgment and reduces them to quantities capable of direct measurement in other floods or at other locations. The application of equation (2) is therefore like the application of the Manning formula, where the value of the roughness-factor n must be selected by judgment from previously measured values. Since equation (2) is based directly on relationships between inflow- and outflow-graphs which necessarily follow from the storage-equation, it will give correct results if correct values of the factors (S_g/Q_s), c, and (t_c/b) are used in its application.

Reference

[1] Robert E. Horton, Virtual channel-inflow graphs, Trans. Amer. Geophys. Union, 1941.

Voorheesville, New York

PROBABILITY-INTERPRETATION OF THE OBSERVED RETURN-PERIODS OF FLOODS

E. J. Gumbel

The purpose of this article is to show by numerical examples how the problem of flood-flows can be treated from the view-point of probability without making any artificial or arbitrary assumptions whatever.

Methods--It is customary in hydrology to calculate either the observed recurrence or the observed exceedance-intervals of floods. In a recent article [see 3 of "References" at end of paper] we have shown that there is only one theoretical value which corresponds to both. We call it the return-period. It is a statistical function as is the distribution or the cumulative frequency. Therefore these calculations are related to the distribution of flows. We have reproduced this distribution by the theory of largest values. As the flood-flows are the largest flows within N = 365 daily observations, this method assumes that N = 365 is a large number and that the discharges can be considered as unlimited statistical variables.

The interpretation of the exceedance- and recurrence-intervals of floods as being the observed return-periods of largest values leads to a formula for the theoretical return-period $T(x)$, in years, as a function of a reduced flood

$$y = \alpha(x - u) \tag{a}$$

where x is the flood-discharge, u the most probable annual flood and $(1/\alpha)$ equal to 98 per cent

Table 1--Observed return-periods, Tennessee River at Chattanooga, 1874-1934

Flood-discharge, x_m	Serial No., m	Return-period, log $'T(x_m)$	Flood-discharge, x_m	Serial No., m	Return-period, log $'T(x_m)$
85.9	1	0.0072	195	31	0.3082
108	2	0.0144	201	32	0.3229
123	3	0.0219	202	33	0.3381
125	4	0.0294	210	34	0.3539
133	5	0.0371	210	35	0.3703
134	6	0.0449	212	36	0.3874
142	7	0.0529	217	37	0.4051
143	8	0.0610	220	38	0.4236
143	9	0.0693	221	39	0.4429
146	10	0.0777	229	40	0.4631
146	11	0.0864	229	41	0.4843
157	12	0.0951	246	42	0.5065
161	13	0.1041	248	43	0.5300
162	14	0.1132	252	44	0.5549
163	15	0.1225	252	45	0.5812
164	16	0.1321	252	46	0.6092
167	17	0.1418	254	47	0.6392
178	18	0.1518	254	48	0.6714
180	19	0.1621	259	49	0.7061
181	20	0.1725	261	50	0.7439
182	21	0.1833	266	51	0.7853
183	22	0.1943	266	52	0.8311
183	23	0.2055	267	53	0.8822
188	24	0.2171	269	54	0.9402
188	25	0.2290	271	55	1.0072
189	26	0.2412	275	56	1.0864
189	27	0.2538	283	57	1.1833
190	28	0.2668	285	58	1.3082
195	29	0.2802	310	59	1.4843
195	30	0.2939	349	60	1.7853
			361	61	......

$\Sigma x_m = 12649.9$ $\Sigma x_m^2 = 2,820,656.81$

Table 2--Observed return-periods, Connecticut River at Hartford, Connecticut, 1843-1891, 1893-1927

Flood-discharge, x_m	Serial No., m	Return-period, log 'T(x_m)	Flood-discharge, x_m	Serial No., m	Return-period, log 'T(x_m)
48	1	0.0052	108	43	0.3115
59	2	0.0105	108	44	0.3222
61	3	0.0158	109	45	0.3332
64	4	0.0212	110	46	0.3445
64	5	0.0267	110	47	0.3561
64	6	0.0322	111	48	0.3680
65	7	0.0378	114	49	0.3802
66	8	0.0435	115	50	0.3928
68	9	0.0492	115	51	0.4058
70	10	0.0551	116	52	0.4191
71	11	0.0610	117	53	0.4329
73	12	0.0670	119	54	0.4472
75	13	0.0730	120	55	0.4619
79	14	0.0792	121	56	0.4771
81	15	0.0855	121	57	0.4929
86	16	0.0918	122	58	0.5093
88	17	0.0982	124	59	0.5264
88	18	0.1048	127	60	0.5441
89	19	0.1114	130	61	0.5626
90	20	0.1181	130	62	0.5819
90	21	0.1250	132	63	0.6021
90	22	0.1319	135	64	0.6233
93	23	0.1390	136	65	0.6455
97	24	0.1461	137	66	0.6690
97	25	0.1535	142	67	0.6939
97	26	0.1609	143	68	0.7202
98	27	0.1684	143	69	0.7482
99	28	0.1761	147	70	0.7782
99	29	0.1839	150	71	0.8104
99	30	0.1919	150	72	0.8451
100	31	0.2000	154	73	0.8829
101	32	0.2083	159	74	0.9243
102	33	0.2167	161	75	0.9701
102	34	0.2253	165	76	1.0212
105	35	0.2341	166	77	1.0792
106	36	0.2431	167	78	1.1461
106	37	0.2522	169	79	1.2253
106	38	0.2615	170	80	1.3222
107	39	0.2711	175	81	1.4472
107	40	0.2808	192	82	1.6233
108	41	0.2908	196	83	1.9243
108	42	0.3011	205	84	......

$\Sigma x_m = 9507$ $\Sigma x_m^2 = 1,171,702$

of the mean deviation. The theoretical return-period T(x) as a function of y is given in Table 9, columns (b) and (a). For T(x) = 10 the asymptote of this function

$$y = \ell n T$$

is almost reached. It is convenient to plot the flows x as a function of the common logarithm of the return-periods, log T. The straight line $x = (u + \ell nT/\alpha)$, which passes through T = 1 and x = u, gives the most probable flood as a function of the number of years T.

From the point of view of the return-period another interpretation of the two constants u and $(1/\alpha)$ can be given; the value u is the flood to which corresponds a return-period T(u) = e : (e - 1) = 1.582. If we let the most probable flood to be reached in ten and 100 years be

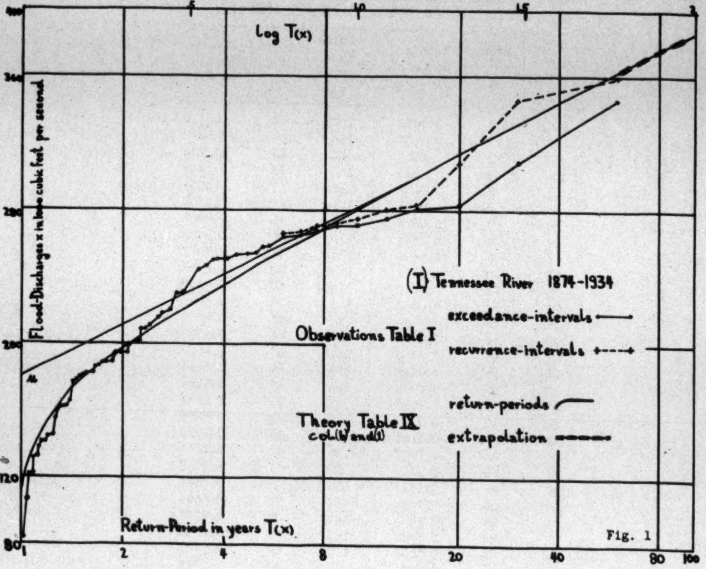

.5
1.0
1.5
2
Log T(x)
400
360
280
200
120
80
Flood-Discharges x in 1000 cubic feet per second
M
(I) Tennessee River 1874-1934
exceedance-intervals
Observations Table I
recurrence-intervals
return-periods
Theory Table IX
col.(b) and (1)
extrapolation
Return-Period in years T(x)
1
2
4
8
20
40
80
100

Fig. 1

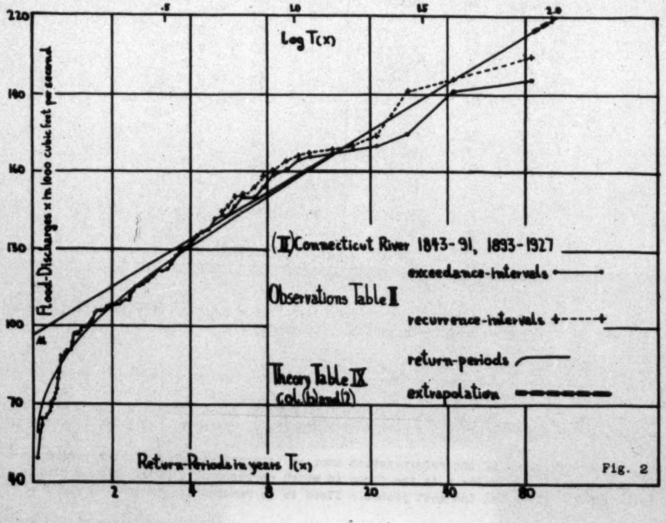

.5
1.0
1.5
2.0
Log T(x)
220
190
160
130
100
70
40
Flood-Discharges x in 1000 cubic feet per second
M
(II) Connecticut River 1843-91, 1893-1927
exceedance-intervals
Observations Table II
recurrence-intervals
return-periods
Theory Table IX
col.(b) and (2)
extrapolation
Return-Periods in years T(x)
2
4
8
20
40
80

Fig. 2

u(10) and u(100) respectively, then

$$(1/\alpha) = 2.30254\,[\,u(100) - u(10)\,]$$

But these relations cannot be used for the numerical determination of the constants. For this purpose we apply the method of moments to the observed distribution.

Our method can be summarized by the following rules:

(1) Take for each year one value, the maximum daily discharge and arrange these n data according to increasing magnitudes. Do not use momentary peaks.

(2) Calculate for each of these flood-discharges $x_m [m = 1.2, \ldots.(n-1)]$, the value $\log T(x_m) = [\log n - \log (n-m)]$ and plot the curves x_m, $\log [n/(n-m)]$, and x_{m+1}, $\log [n/(n-m)]$. These are the observed exceedance- and the observed recurrence-intervals. m is called the serial number. The exceedance-intervals start with x_1, $\log [n/(n-1)]$ and end with x_{n-1}, $\log n$. There is no exceedance-interval corresponding to the largest value x_n. The recurrence-intervals start with x_1, 0 and end with x_n, $\log n$. For given x_m, of course, the exceedance-interval surpasses the recurrence-interval. But this difference is small, unless m is large.

(3) Calculate the annual mean flood

$$\bar{u} = (1/n) \sum_{m=1}^{n} x_m \tag{1}$$

the annual mean squared flood

$$\overline{u^2} = (1/n) \sum_{m=1}^{n} x_m^2 \tag{2}$$

the standard deviation

$$s = \sqrt{[1 + 1/(n-1)][\overline{u^2} - (\bar{u})^2]} \tag{3}$$

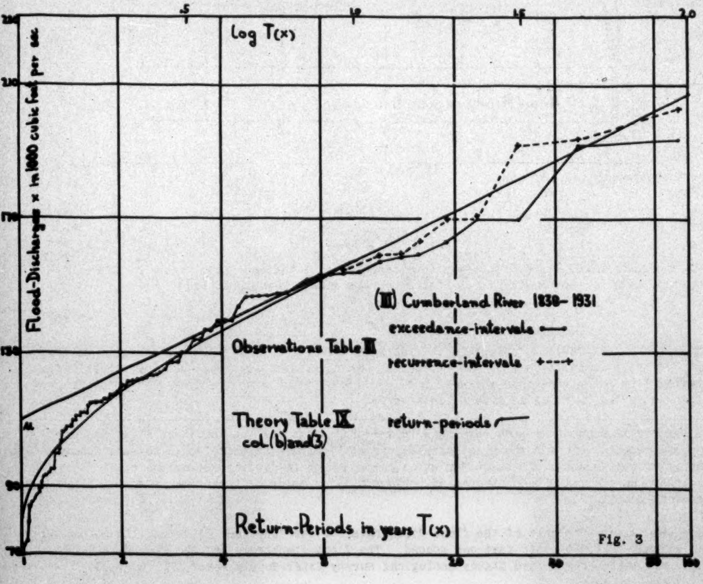


Fig. 3

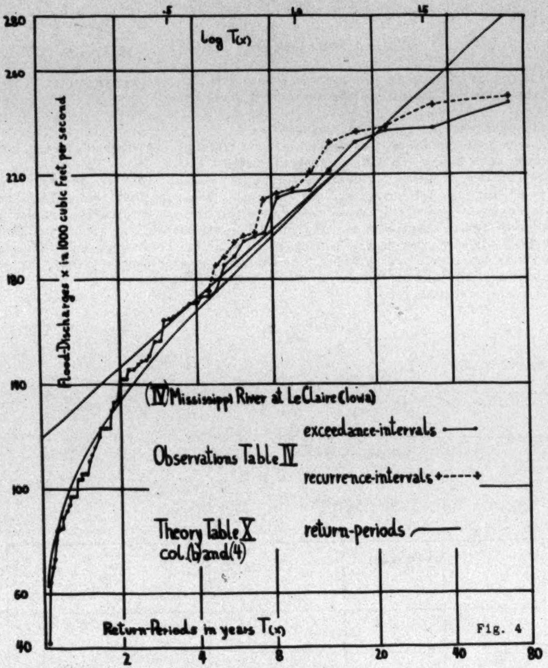


Fig. 4

and the two constants

$$1/\alpha = 0.77970\ s \tag{4}$$

$$u = \bar{u} - 0.45005\ s \tag{5}$$

(4) The theoretical flood-discharges x corresponding to the logarithm of the return-period T(x) given in Table 9, column (b), are obtained by the linear transformation

$$x = (u + y/\alpha) \tag{6}$$

where y is taken from Table 9, column (a). Plot x as a function of log T(x). For large values of x and for the extrapolation it is sufficient to use the linear asymptote obtained graphically. The straight line which goes from the most probable annual flood u to the linear asymptote represents the most probable flood as a function of time.

In our previous paper we have shown how this method works for the Merrimack River at Lawrence, Massachusetts, and for the Mississippi River at Vicksburg, Mississippi. We will consider now some other representative streams for which numerous and reliable observations exist. Some of the streams have already been studied by various authors using different methods and obtaining different results.

Tennessee River--The unit of the flood-discharges for the Tennessee River and the following American streams is 1,000 cubic feet per second. The flood-discharges for the Tennessee River, 1874-1934, are taken from United States Geological Survey Water-Supply Paper 771, page 204.

Table 1, column (1), gives the n = 61 values of x_m arranged according to increasing magnitude, column (2) gives the serial number m, and column (3) gives for m = 1,2,.....61, the logarithm of the observed return-periods log [61/(61 - m)]. The observed exceedance-intervals x_m, log 'T (x_m) and the observed recurrence-intervals x_{m+1}, log 'T (x_m) are plotted in Figure 1.

In order to draw the theoretical curve we determine the constants. The sum of the flood-discharges is

$$\sum_{m=1}^{61} x_m = 12649.9$$

From equation (1) we obtain the annual mean flood $\bar{u}$ = 207.375 [Table 8, column (1)].

The sum of the x squares is

$$\sum_{m=1}^{61} x_m^2 = 2820656.81$$

whence from equation (2) [Table 8, column (1)]

$$\overline{u^2} = 46240.276$$

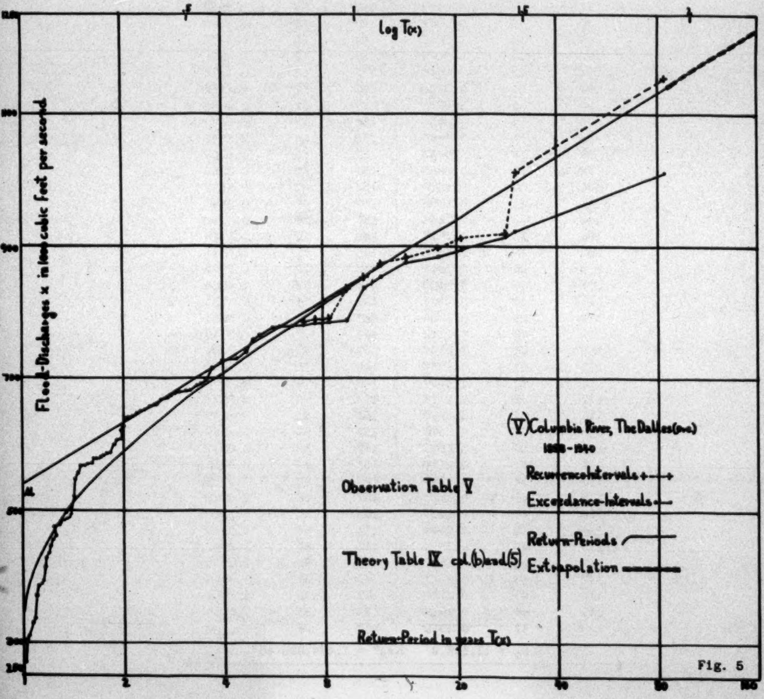


Fig. 5

and from equation (3) the standard deviation [Table 8, column (1)]

$$s = 57.355$$

From equation (4) and (5) we obtain the constant $(1/\alpha) = 44.357$ and the most probable annual flood $u = 183.378$ [Table 8, column (1)]. Therefore the theoretical floods x corresponding to the

Table 3--Observed return-periods, Cumberland River at Nashville, Tennessee, 1838-1931

Flood-discharge, x_m	Serial No., m	Return-period, $\log {}'T(x_m)$	Flood-discharge, x_m	Serial No., m	Return-period, $\log {}'T(x_m)$
69	1	0.0046	120	48	0.3103
72.4	2	0.0103	121	49	0.3209
73.4	3	0.0141	121	50	0.3296
79.2	4	0.0189	121	51	0.3396
80.4	5	0.0237	122	52	0.3499
84.8	6	0.0286	122	53	0.3603
86	7	0.0336	122	54	0.3710
86.4	8	0.0386	123	55	0.3820
86.5	9	0.0437	123	56	0.3933
89	10	0.0488	123	57	0.4049
89.3	11	0.0540	124	58	0.4168
90.9	12	0.0593	125	59	0.4290
92.8	13	0.0646	127	60	0.4416
93	14	0.0700	127	61	0.4556
93	15	0.0755	127	62	0.4680
94	16	0.0810	130	63	0.4827
95	17	0.0866	130	64	0.4960
95.1	18	0.0923	131	65	0.5107
99.9	19	0.0980	134	66	0.5259
100	20	0.1039	134	67	0.5417
101	21	0.1098	137	68	0.5581
104	22	0.1148	137	69	0.5752
106	23	0.1218	140	70	0.5929
107	24	0.1280	140	71	0.6114
108	25	0.1343	140	72	0.6307
108	26	0.1406	144	73	0.6509
110	27	0.1470	147	74	0.6721
110	28	0.1536	147	75	0.6943
111	29	0.1602	147	76	0.7178
111	30	0.1669	147	77	0.7427
112	31	0.1738	148	78	0.7690
112	32	0.1807	148	79	0.7970
112	33	0.1878	152	80	0.8270
114	34	0.1949	152	81	0.8592
115	35	0.2022	153	82	0.8939
115	36	0.2097	153	83	0.9317
115	37	0.2172	154	84	0.9731
115	38	0.2249	154	85	1.0189
115	39	0.2327	157	86	1.0700
115	40	0.2407	159	87	1.1280
116	41	0.2488	159	88	1.1949
116	42	0.2571	163	89	1.2741
117	43	0.2655	170	90	1.3710
117	44	0.2741	170	91	1.4960
118	45	0.2829	192	92	1.6721
119	46	0.2919	194	93	1.9731
120	47	0.3010	203	94	......
	$\Sigma x_m = 11{,}503.9$		$\Sigma x_m^2 = 1{,}474{,}890.45$		

the return-periods $T(x)$, given in Table 9, column (b), are, according to equation (6)

$$x = 183.378 + 44.357\, y$$

The floods obtained by letting y increase from -1.5 to 4.0 are given in Table 9, column (1). The theoretical values x, $\log T(x)$ are traced in Figure 1. The logarithm of the return-periods and the return-periods in years are represented on the horizontal axis. The flood-discharges and the most probable annual flood are represented on the vertical axis. The straight line through u gives the most probable flood x as a function of time. The theoretical return-periods agree satisfactorily with the observations.

Other American streams--Flood-data and computations made according to the above methods for the Connecticut, Cumberland, Mississippi, and Columbia rivers are given in Tables 2 to 5. (These data have been put at my disposal through the courtesy of Clarence C. Jarvis of the Department of Agriculture.) The constants for the four streams are shown in Table 8. The different theoretical floods corresponding to the common theoretical return-period $T(x)$ are given in Table 9, columns (2) to (5). For each stream there are plotted in Figures 2 to 5 the observed (broken lines) and theoretical (continuous lines) return-periods.

Table 4--Observed return-periods, Mississippi River at Le Claire, Iowa, 1873-1934 [and other years, see Table 8]

Flood-discharge, x_m	Serial No., m	Return-period, log $'T(x_m)$	Flood-discharge, x_m	Serial No., m	Return-period, log $'T(x_m)$
40.7	1	0.0064	142	35	0.3140
64.3	2	0.0130	142	36	0.3274
70	3	0.0196	146	37	0.3411
73.1	4	0.0263	146	38	0.3554
80	5	0.0333	148	39	0.3701
83.6	6	0.0401	149	40	0.3853
85.3	7	0.0472	149	41	0.4011
85.3	8	0.0543	151	42	0.4175
88.8	9	0.0616	157	43	0.4346
92	10	0.0691	157	44	0.4523
92.1	11	0.0766	160	45	0.4708
93.9	12	0.0843	165	46	0.4901
96.8	13	0.0921	166	47	0.5103
97.5	14	0.1001	167	48	0.5315
97.5	15	0.1082	169	49	0.5537
98.4	16	0.1165	171	50	0.5772
104	17	0.1249	172	51	0.6021
104	18	0.1335	174	52	0.6284
106	19	0.1423	174	53	0.6564
106	20	0.1513	176	54	0.6864
106	21	0.1604	186	55	0.7186
111	22	0.1697	189	56	0.7533
113	23	0.1793	195	57	0.7911
116	24	0.1890	197	58	0.8325
120	25	0.1990	198	59	0.8783
120	26	0.2093	212	60	0.9294
123	27	0.2193	214	61	0.9874
123	28	0.2304	214	62	1.0543
123	29	0.2414	222	63	1.1335
123	30	0.2527	233	64	1.2304
130	31	0.2643	237	65	1.3554
133	32	0.2762	238	66	1.5315
134	33	0.2884	248	67	1.8325
142	34	0.3010	250	68	......

$\Sigma x_m = 9{,}691.1 \quad \Sigma x_m^2 = 1{,}543{,}559.73$

Table 5--Observed return-periods, Columbia River at The Dallas, 1858-1940

Flood-discharge, x_m	Serial No., m	Return-period, log $'T(x_m)$	Flood-discharge, x_m	Serial No., m	Return-period, log $'T(x_m)$
269	1	0.0053	629	42	0.3063
302	2	0.0106	633	43	0.3170
308	3	0.0160	638	44	0.3280
328	4	0.0215	642	45	0.3393
328	5	0.0270	643	46	0.3509
332	6	0.0326	644	47	0.3628
369	7	0.0383	649	48	0.3750
374	8	0.0440	653	49	0.3876
376	9	0.0499	654	50	0.4006
387	10	0.0558	662	51	0.4140
412	11	0.0618	668	52	0.4277
428	12	0.0678	671	53	0.4420
433	13	0.0740	673	54	0.4567
448	14	0.0803	675	55	0.4719
453	15	0.0866	677	56	0.4877
460	16	0.0930	679	57	0.5041
475	17	0.0996	684	58	0.5212
476	18	0.1062	690	59	0.5389
482	19	0.1129	698	60	0.5574
483	20	0.1198	714	61	0.5767
485	21	0.1267	722	62	0.5969
486	22	0.1338	727	63	0.6181
493	23	0.1409	727	64	0.6403
519	24	0.1482	737	65	0.6637
547	25	0.1557	759	66	0.6887
553	26	0.1632	766	67	0.7150
563	27	0.1709	773	68	0.7430
564	28	0.1787	777	69	0.7730
565	29	0.1867	777	70	0.8052
566	30	0.1948	780	71	0.8399
568	31	0.2031	785	72	0.8777
573	32	0.2115	787	73	0.9191
574	33	0.2201	787	74	0.9649
578	34	0.2289	839	75	1.0160
581	35	0.2379	856	76	1.0740
582	36	0.2470	874	77	1.1409
587	37	0.2563	883	78	1.2201
598	38	0.2659	896	79	1.3170
605	39	0.2756	914	80	1.4420
607	40	0.2856	919	81	1.6181
618	41	0.2959	1020	82	1.9191
			1160	83	......

$\Sigma x_m = 51,266 \qquad \Sigma x_m^2 = 34,123,942$

Rhine and Rhone--As last examples we apply our method to two European streams for which numerous observations exist. The Tables 6 and 7 give the observed return-periods of the flood-discharges for the Rhine at Basel 1808-1933, reported by Ghezzi [2], and for the Rhone at Lyon 1826-1939, reported by Coutagne [1]. For these two streams the unit of measurement is cubic meters per second. The constants are to be found in Table 8 and the theoretical floods in Table 9, columns (6) and (7). In Figures 6 and 7 are shown the theoretical and the observed values.

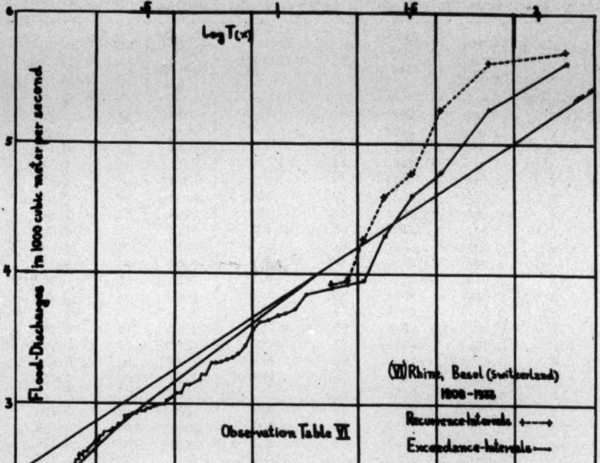

Log T(x)
Flood-Discharges in 1000 cubic meter per second
(VI) Rhine, Basel (Switzerland) 1808-1936
Recurrence-intervals
Exceedance-intervals
Return-Periods
Extrapolation
Observation Table VI
Theory Table IX col(6) and (8)
Return-Period T(x) in years
.5
1
1.5
2
3
4
5
6
1.4
2
4
8
20
40
80
100

Fig. 6

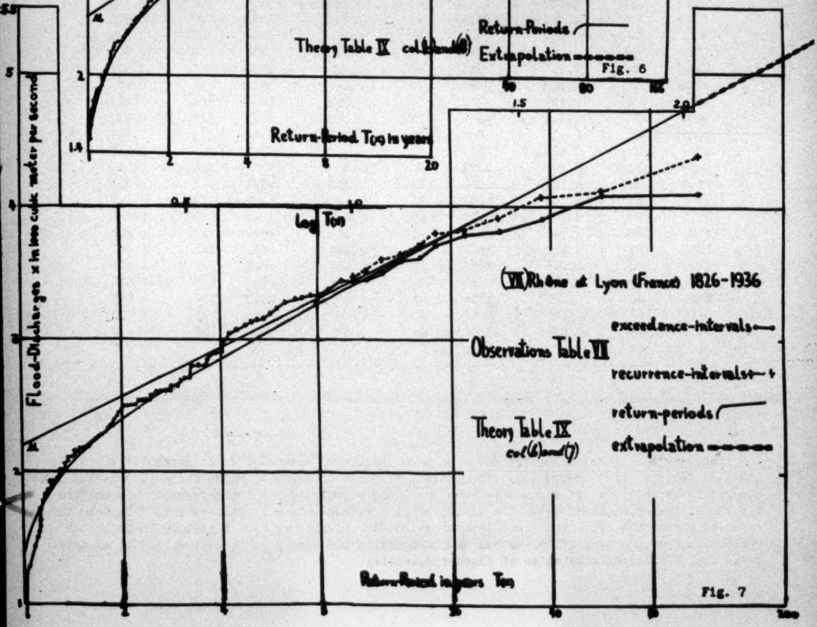

5.5
5
4
3
2
1
0.5
1.0
1.5
2.0
Log T(x)
Flood-Discharges x in 1000 cubic meter per second
(VII) Rhône at Lyon (France) 1826-1936
exceedance-intervals
Observations Table VII
recurrence-intervals
return-periods
Theory Table IX col(6) and (7)
extrapolation
Return-Period in years T(x)
2
4
8
20
40
80
100

Fig. 7

Table 6--Observed return-periods, Rhine River at Basle, Switzerland, 1808-1933

Flood-discharge, x_m	Serial No., m	Return-period, log 'T(x_m)	Flood-discharge, x_m	Serial No., m	Return-period, log 'T(x_m)	Flood-discharge, x_m	Serial No., m	Return-period, log 'T(x_m)
1487	1	0.004	2424	43	0.181	2954	85	0.488
1603	2	0.007	2424	44	0.187	2964	86	0.498
1724	3	0.010	2451	45	0.192	2964	87	0.509
1747	4	0.014	2469	46	0.197	2984	88	0.521
1790	5	0.018	2478	47	0.203	2984	89	0.532
1793	6	0.021	2506	48	0.208	2994	90	0.544
1864	7	0.025	2506	49	0.214	2994	91	0.556
1864	8	0.029	2533	50	0.220	3044	92	0.569
1880	9	0.032	2561	51	0.225	3054	93	0.582
1900	10	0.036	2561	52	0.231	3064	94	0.595
1904	11	0.040	2561	53	0.237	3085	95	0.609
1912	12	0.044	2598	54	0.243	3095	96	0.623
1912	13	0.047	2598	55	0.249	3156	97	0.638
1985	14	0.051	2635	56	0.255	3156	98	0.653
1985	15	0.055	2635	57	0.262	3167	99	0.669
2001	16	0.059	2645	58	0.268	3197	100	0.685
2034	17	0.063	2654	59	0.274	3239	101	0.703
2068	18	0.067	2673	60	0.281	3240	102	0.720
2076	19	0.071	2692	61	0.288	3322	103	0.739
2093	20	0.075	2702	62	0.294	3322	104	0.758
2118	21	0.079	2702	63	0.301	3333	105	0.778
2169	22	0.083	2702	64	0.308	3354	106	0.799
2186	23	0.088	2721	65	0.315	3360	107	0.822
2190	24	0.092	2760	66	0.322	3396	108	0.845
2203	25	0.096	2780	67	0.330	3460	109	0.870
2220	26	0.100	2780	68	0.337	3590	110	0.896
2229	27	0.105	2788	69	0.345	3623	111	0.924
2238	28	0.109	2788	70	0.352	3656	112	0.954
2238	29	0.114	2800	71	0.360	3689	113	0.987
2238	30	0.118	2807	72	0.368	3700	114	1.021
2255	31	0.123	2807	73	0.376	3745	115	1.059
2264	32	0.127	2827	74	0.384	3857	116	1.100
2290	33	0.132	2827	75	0.393	3891	117	1.146
2308	34	0.137	2864	76	0.401	3903	118	1.197
2317	35	0.141	2905	77	0.410	3925	119	1.255
2334	36	0.146	2905	78	0.419	3960	120	1.322
2343	37	0.151	2905	79	0.428	4300	121	1.401
2370	38	0.156	2925	80	0.438	4615	122	1.498
2378	39	0.161	2930	81	0.447	4790	123	1.623
2379	40	0.166	2934	82	0.457	5280	124	1.799
2415	41	0.171	2945	83	0.467	5642	125	2.100
2424	42	0.176	2954	84	0.477	5700	126	.....

$\Sigma x_m = 352{,}138 \qquad \Sigma x_m^2 = 1{,}055{,}620{,}370$

Tables--The constants for the seven streams calculated according to formulas (1) to (5) are given in Table 8. The theoretical flood-flows, x, given in Table 9, which correspond to the common return-periods T(x) of Table 9 [column (b)], are calculated for the different streams from the linear transformations (6). The satisfactory agreement shown in Figures 1 to 7 between the observed exceedance- and recurrence-intervals and the theoretical return-periods leads to the conclusion that the statistical method and especially the theory of largest values is an adequate tool for the determination of flood-frequencies.

Table 7--Observed return-periods, Rhone River at Lyon, France, 1826-1936

Flood-discharge, x_m	Serial No., m	Return-period, log $'T(x_m)$	Flood-discharge, x_m	Serial No., m	Return-period, log $'T(x_m)$
899	1	0.004	2475	57	0.313
1172	2	0.008	2475	58	0.321
1231	3	0.012	2475	59	0.329
1272	4	0.016	2491	60	0.338
1272	5	0.020	2514	61	0.346
1432	6	0.024	2514	62	0.355
1432	7	0.028	2514	63	0.364
1439	8	0.032	2514	64	0.373
1444	9	0.037	2538	65	0.382
1502	10	0.041	2554	66	0.392
1541	11	0.045	2586	67	0.402
1560	12	0.050	2594	68	0.412
1639	13	0.054	2594	69	0.422
1706	14	0.058	2594	70	0.432
1780	15	0.063	2602	71	0.443
1829	16	0.068	2626	72	0.454
1850	17	0.072	2627	73	0.465
1857	18	0.077	2643	74	0.477
1913	19	0.081	2675	75	0.489
1913	20	0.086	2675	76	0.501
1934	21	0.091	2773	77	0.514
1955	22	0.096	2773	78	0.527
1992	23	0.101	2773	79	0.540
1992	24	0.106	2839	80	0.554
2006	25	0.111	2856	81	0.568
2006	26	0.116	2881	82	0.583
2013	27	0.121	2881	83	0.598
2050	28	0.126	2965	84	0.614
2050	29	0.131	3007	85	0.630
2072	30	0.137	3050	86	0.647
2094	31	0.142	3058	87	0.665
2101	32	0.148	3067	88	0.684
2115	33	0.153	3067	89	0.703
2145	34	0.159	3126	90	0.723
2145	35	0.164	3179	91	0.744
2153	36	0.170	3214	92	0.766
2160	37	0.176	3258	93	0.790
2168	38	0.182	3266	94	0.825
2175	39	0.188	3293	95	0.841
2206	40	0.194	3310	96	0.869
2206	41	0.200	3310	97	0.899
2206	42	0.206	3354	98	0.931
2221	43	0.213	3426	99	0.966
2236	44	0.219	3444	100	1.004
2240	45	0.226	3444	101	1.045
2258	46	0.232	3480	102	1.091
2281	47	0.239	3606	103	1.142
2296	48	0.246	3625	104	1.200
2327	49	0.253	3708	105	1.267
2342	50	0.260	3801	106	1.346
2358	51	0.267	3810	107	1.443
2381	52	0.274	3905	108	1.568
2420	53	0.282	4096	109	1.744
2444	54	0.289	4105	110	2.045
2452	55	0.297	4390	111	.....
2467	56	0.305			

$\Sigma x_m = 276{,}773$ $\Sigma x_m^2 = 744{,}538{,}565$

Table 8--Numerical constants

Item No.	Item	Symbol	Formula	River and station: Tennessee, Chattanooga, Table 1	Connecticut, Hartford, Table 2	Cumberland, Nashville, Table 3
1	Authority	...	...	Floods, p. 204	Hazen, p. 29	Floods, p. 198
2	Years	...	...	1874-1934	1843-91;1893-1927	1838-1931
3	No. observations	n	...	61	84	94
4	Annual mean flood	$\bar{u}$	(1)	207,375	113,179	122,382
5	Mean-squared flood	$\overline{u^2}$	(2)	46,240,276	13,948,833	15,690,324
6	Standard deviation	s	(3)	57,355	33,958	26,845
7	Constant	$1:\alpha$	(4)	44,720	26,477	20,931
8	Most probable annual flood	u	(5)	181,562	97,895	110,300

Item No.	Symbol	Formula	River and station: Mississippi, Le Claire, Table 4	Columbia, The Dallas, Table 5	Rhine, Basel, Table 6	Rhône, Lyon, Table 7
1	...	...	Floods, p. 239	Floods, p. 381	Ghezzi	Coutagne
2	...	...	1861,2,6,7;1870-71; 1873-1934	1858-1940	1808-1933	1826-1936
3	n	...	68	83	126	111
4	$\bar{u}$	(1)	142,516	17.66	2,794.75	2,493.45
5	$\overline{u^2}$	(2)	22,699.42	411,318.31	8,377,939	6,707,555
6	s	(3)	49,236	3,709	756.22	703.08
7	$1:\alpha$	(4)	38,389	35.44	589.62	548.19
8	u	(5)	120,357	39.48	2,454.05	2,177.03

Table 9--The theoretical return-periods for seven streams

Reduced flood y (a)	Return-period log T(x) (b)	Return-period flood, x, for river						
		Tennessee (1)	Connecticut (2)	Cumberland (3)	Mississippi (4)	Columbia (5)	Rhine (6)	Rhône (7)
-1.5	0.005	114.5	58.2	78.9	62.77	336.3	1570	1355
-1.25	0.013	125.7	64.8	84.1	72.37	370.2	1717	1492
-1.00	0.030	136.8	71.4	89.4	81.97	404.0	1865	1629
-0.75	0.056	148.0	78.0	94.6	91.57	437.9	2012	1766
-0.50	0.093	159.2	84.7	99.8	101.2	471.8	2160	1903
-0.25	0.141	170.4	91.3	105.1	110.8	505.6	2307	2040
0	0.199	181.6	97.9	110.3	120.4	539.5	2454	2177
0.25	0.267	192.7	104.5	115.5	130.0	573.3	2602	2314
0.50	0.342	203.9	111.1	120.8	139.6	607.2	2749	2451
0.75	0.424	215.1	117.8	126.0	149.1	641.1	2897	2588
1.00	0.512	226.3	124.4	131.2	158.7	674.9	3044	2725
1.25	0.604	237.5	131.0	136.5	168.3	708.8	3191	2862
1.50	0.699	248.6	137.6	141.7	177.9	742.6	3339	2999
1.75	0.797	259.8	144.2	146.9	187.5	776.5	3486	3136
2.00	0.898	271.0	150.9	152.1	197.1	810.4	3634	3273
2.25	1.000	282.2	157.5	157.4	206.7	844.2	3781	3410
2.50	1.103	293.4	164.1	162.6	216.3	878.1	3928	3547
2.75	1.208	304.5	170.7	167.9	225.9	911.9	4076	3686
3.00	1.314	315.7	177.3	173.1	235.5	945.8	4223	3822
3.25	1.420	326.9	183.9	178.3	245.1	979.9	4371	3959
3.50	1.527	338.1	190.6	183.6	254.7	1013.5	4518	4096
3.75	1.634	349.3	197.2	188.8	264.3	1047.4	4666	4233
4.00	1.741	360.4	203.8	194.0	273.9	1081.2	4813	4370

References

[1] A. Coutagne, Etude statistique et analytique des crues du Rhône à Lyon, C.-R. du Congrès pour l'utilisation des eaux, Lyon, 1938.

[2] C. Ghezzi, Die Abflussverhältnisse des Rheins in Basel, Mitteilungen des Amts für Wasserwirtschaft, Bern, 1936.

[3] E. J. Gumbel, The return period of flood flows, Ann. Math. Statistics, v. 12, Baltimore, 1941.

[4] Allan Hazen, Flood flows, New York, 1930.

[5] Cl. S. Jarvis and others, Floods in the United States, U. S. Geol. Surv. W.-S. Paper 771.

New School for Social Research,
New York, New York

DISCUSSION

RALPH W. POWELL (Ohio State University, Columbus, Ohio; communicated)--The question of flood-frequency is not of the same relative importance as it was when Fuller first wrote on the subject in 1914. Then the principal design-problems were the provision of adequate levees, spillways, and bridge-openings. Now we are more likely to be concerned with the storage required to reduce flows to a certain allowable maximum, and this depends upon the total volume of the flood-runoff rather than on its peak-value. However there are still cases where the maximum uncontrolled flow must be estimated, and it seems that Dr. Gumbel's method has definite advantages over the several other methods that have been proposed. Dean Saville [A study of the methods of estimating flood flows applied to the Tennessee River, U. S. Geol. Surv. W.-S. Paper 771, pp. 398-420, 1936] has compared various methods and finds that the Slade method has the advantage of requiring the least computation and still giving satisfactory results. But Dr. Gumbel's method also involves only the first and second moments, and does not require the other assumed constants of the Slade method.

By pure mathematical deduction, Dr. Gumbel (in the longer article in the 1941 Annals of Mathematical Statistics) has shown that the flow which may be expected to occur on the average every T years is given by an equation which may be put in the form $y = -\ell n\left\{-\ell n\,[1 - (1/T)]\right\}$, where ℓn means logarithm to the base e, and y is a function of the flow which can be computed from the known maximum annual flows and the formulas given in this paper. He also points out that where T is more than 10 or 20 years the above formula may be shortened to $y = \ell n\,T$ without appreciable error. The values of the logarithms of T corresponding to a number of values of y are tabulated in the first two columns of Table 9. The writer has also computed the values of y corresponding to given values of T in the following Table A.

Table A--Values of y corresponding to values of T

T, years	y	x, Connecticut River at Hartford, in 1000 c f s	Times exceeded in 100 years	
			Expected	Observed
1	$-\infty$	.....		
2	0.3765	107.9	50	
5	1.5000	137.6	20	21
10	2.2504	157.5	10	14
20	2.9703	176.5	5	5
50	3.9019	201.2	2	3
100	4.6002	219.7	1	2
200	5.2958	238.1	0.5	2
500	6.2136	262.4	0.2	1
1000	6.9073	280.8	0.1	1

The maximum flow to be expected in T years is given by equation (6) with the help of equations (3), (4), and (5). In the case of the Connecticut River at Hartford, the author's data reduce to $x = (97.89 + 26.48\,y)$ and the values of x have been listed in Table A. Also the number of times these values have been exceeded in the last 100 years have been tabulated for the periods of five years and higher. These include the 18 highest flows listed in the paper, and those for 1933, 1936, and 1938. It is noteworthy that the maximum calendar-day flow for 1936 (286,000 c f s) and 1938 (242,000 c f s), both far exceed anything in the preceding 300 years. If they had been included in the data used in computing the standard deviation s, and the modal flow u, the agreement of the observed number of flows with the agreed would have been better.

The writer sees no reason why this method should not be applied to the maximum peak-flow of each year, as well as to the maximum calendar-day flow. In smaller streams the latter depends too much on whether the flood happens to peak near midnight or near noon, to be entirely satisfactory.

E. J. GUMBEL (communicated)--The flood x as a function of the return-period T can be obtained in the following simple way. Table 9 gives the reduced value y as function of $\log T(x)$. According to formulas (a), (4), and (5) the reduced value y is related to the reduced value $z = (x - \bar{u}) : s$, often used in statistics, by

$$z = 0.77970\,y - 0.45005 \tag{7}$$

We substitute for y the numbers given in Table 9 and obtain $z(T)$ as a function of $\log T$. These values are plotted in Figure 8. The linear asymptote $y = \ell n T$ becomes $z = 1.79532 \log T - 0.45005$. The most probable flood to be reached within T years is $x = \bar{u} - 0.45005\,s + 1.79532\,s \log T = \bar{u} + 1.79532\,s \log (0.56146\,T)$.

This line is plotted in Figure 8, which shows the reduced flood z as a function of the return-period T. For a given stream, having the mean annual flood $\bar{u}$ and the standard deviation s, the flood x corresponding to a return-period T is

$$x = \bar{u} + s\,z(T) \tag{8}$$

The mean annual flood $\bar{u}$ plus one, two, and three times the standard deviation s has a return-period of 7.1, 23.5, and 83.5 years, respectively.

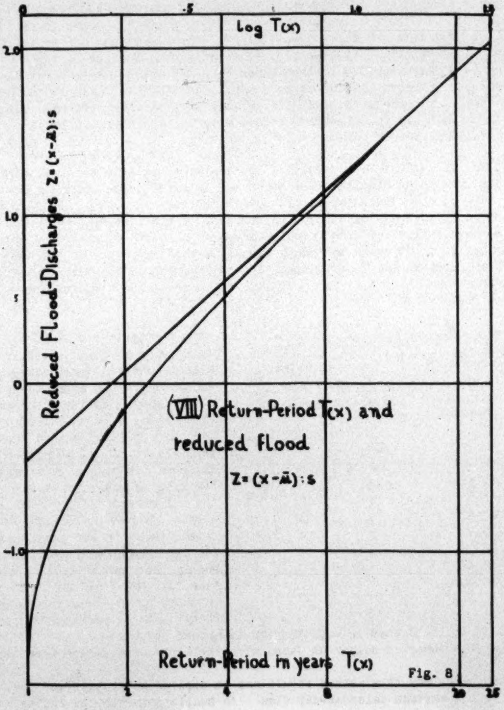


Fig. 8

PERIOD VERSUS INSTANTANEOUS DISTRIBUTION-COEFFICIENTS

Waldo E. Smith

It has long been the practice for hydraulic engineers and hydrologists to form a hydrograph at a confluence by adding average flows of the tributaries for a day or less. In connection with some channel-flood routing methods, instantaneous values are preferable to average period values, and in some instances the writer has, with some feeling of uncertainty as to results, added instantaneous ordinates of two or more plotted hydrographs.

With the development and use of the unit-hydrograph and the distribution-graph, average ordinates of flow resulting from given rains for successive periods of time have been added to obtain the total average flow for the successive periods. Although the writer has seen a number of instances in which the summations for a succession of periods have been incorrectly used as though they were instantaneous values, the correct interpretation of the usual application of distribution-coefficients is to plot the computed hydrograph as a block-graph of the period-summations and then proceed to draw a smooth curve through these blocks, having beneath it in each period the same area as that within the corresponding block.

In their work on the unit graph, Morgan and Hullinghorst [R. Morgan and D. W. Hullinghorst, Unit hydrolgraphs for gaged and ungaged watersheds, unpublished manuscript, U. S. Eng. Office, Binghamton, N. Y., July 1, 1939] added instantaneous values of unit-graphs plotted a unit-period apart to secure their S-curve. The resulting curve was a wavy line which was subsequently smoothed out. The use of average-period values would have tended to eliminate the waviness, and it would appear that period-averages might have served their purposes better.

In connection with recent flood-control studies on the East Fork of Trinity River in Texas, a considerable mass of work involving the use of distribution-graphs was in prospect, to be handled in short order by a relatively small staff. It was therefore decided to attempt to use, not period-average distribution-coefficients, but rather instantaneous ones read from a plotting of the graph as a smooth curve at the dividing points between the successive periods. Work proceeded on this basis, checking a limited amount of the work by application of the period distribution-coefficients in the usual manner. The results of this comparison are set forth in this paper.

The East Fork of the Trinity River (Fig. 1) comprises 1,350 square miles of the relatively homogeneous Blacklands in northeastern Texas. It is gaged by the United States Geological Survey by a chain-gage near Rockwall, at which point the drainage-area is 831 square miles. In connection with the Department of Agriculture flood-control investigations, it was necessary to derive the distribution-graph for this station, as well as a number of synthetic graphs for smaller areas upstream. The technique by which the synthetic distribution graphs were derived is not within the scope of this paper. It should be mentioned, however, that it was found that the distribution-graph for the station at Rockwall varied considerably for various amounts of precipitation-excess falling within a given period and that it was necessary to derive a crest and lag correction-factors for different amounts of precipitation excess in a definite proportion of the lag-time. This is mentioned because it eliminates the possibility of making certain checks on the results of this comparison by a further comparison with observed hydrographs.

Figure 1 is a map of the East Fork of the Trinity River showing the ten areas into which the area above the Rockwall gaging-station was divided for purposes of hydrologic analysis. Areas 1, 2, 3, 6, and 8 are primary watersheds whereas 4, 5, 9, and 10 are sub-watersheds. Area 7 is likewise a sub-watershed, but inasmuch as it is for the most part a single primary watershed it was treated as such. Areas 1, 2, and 4 combine to form a primary watershed designated as $\Sigma 4$. Other combinations were similarly made and the watershed as a whole was designated as $\Sigma 10$.

Figure 2 shows the distribution-graphs derived for the successive primary watersheds on and flowing into the main stream. These are in the form from which both period and instantaneous distribution coefficients were determined.

Figure 3 shows the computed hydrographs for the flood of June, 1935, for the primary watersheds involved in the analysis. The cross-hatched areas represent the areal average amount of precipitation-excess ascribed to the successive periods of time. The solid stepped lines show the block-hydrographs computed from the period distribution-coefficients. The estimated hydrographs determined from the blocks are shown by the solid lines, while the hydrographs as determined by the instantaneous distribution-coefficients are shown by the dashed lines, with the computed points shown by the small circles. The solid line was drawn prior to the plotting of

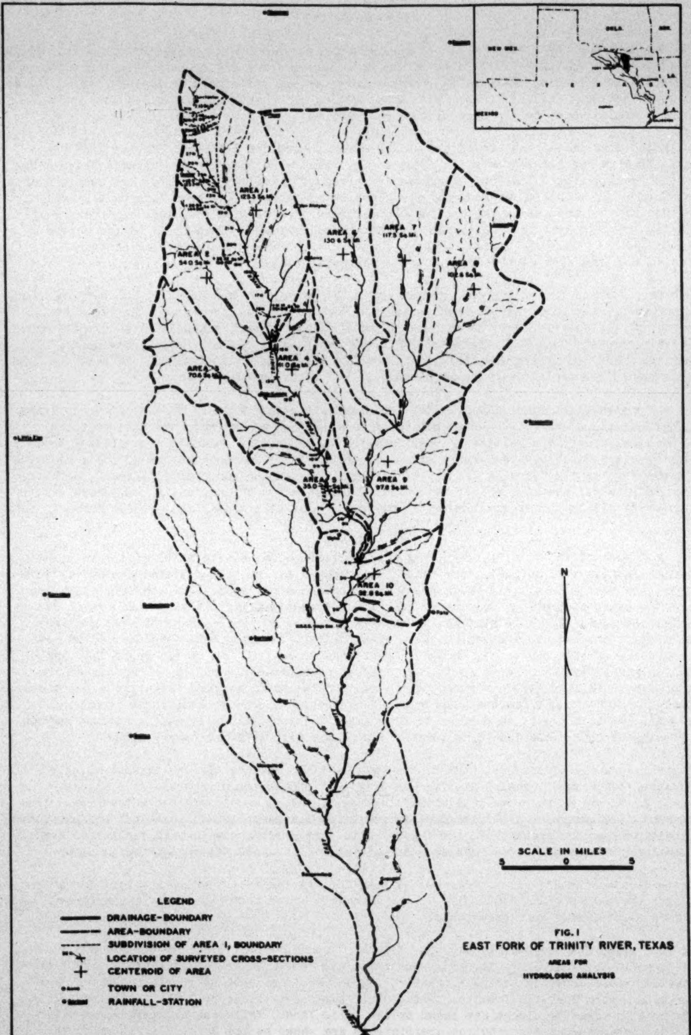

OKLA.
ARK.
NEW MEX.
T E X A S
LA.
MEXICO
AREA 1
125.3 Sq.Mi.
AREA 2
54.0 Sq.Mi.
AREA 3
70.6 Sq.Mi.
AREA 4
51.0 Sq.Mi.
AREA 5
35.0 Sq.Mi.
AREA 6
130.6 Sq.Mi.
AREA 7
117.3 Sq.Mi.
AREA 8
102.6 Sq.Mi.
AREA 9
97.8 Sq.Mi.
AREA 10
32.8 Sq.Mi.
EAST FORK
TRINITY RIVER
N
SCALE IN MILES
5 0 5
LEGEND
DRAINAGE-BOUNDARY
AREA-BOUNDARY
SUBDIVISION OF AREA 1, BOUNDARY
LOCATION OF SURVEYED CROSS-SECTIONS
CENTEROID OF AREA
TOWN OR CITY
RAINFALL-STATION

FIG. 1
EAST FORK OF TRINITY RIVER, TEXAS
AREAS FOR HYDROLOGIC ANALYSIS

the points secured for the instantaneous coefficients. General agreement is excellent, and in most cases the crest-values derived by the two methods agree quite closely.

The following tentative conclusions are offered:

(1) Better definition of the hydrograph, especially the crest, may be secured by means of instantaneous distribution-coefficients as there is less latitude in drawing the hydrograph. One exception to this would be the case in which none of the distribution-coefficients is a value near the crest as shown by the hydrograph for area 3 on Figure 3. This difficulty may usually be overcome by the analysis suggested in conclusion (2) below.

(2) Any other uniform intervals of time, either longer or shorter than the period for which the distribution-graph is defined may be used. Ordinarily this should be shorter in order to secure better definition, especially of the crest, and one should usually use such a time-value that some multiple is equal to the period for which the distribution-graph was derived.

(3) The saving in time is relatively great. It is not necessary for one to plot the hydrograph unless other work requires that this be done. In any case, the matter of plotting a block-hydrograph and then drawing a curve approximating the actual hydrograph and subsequently reading off desired instantaneous values is eliminated.

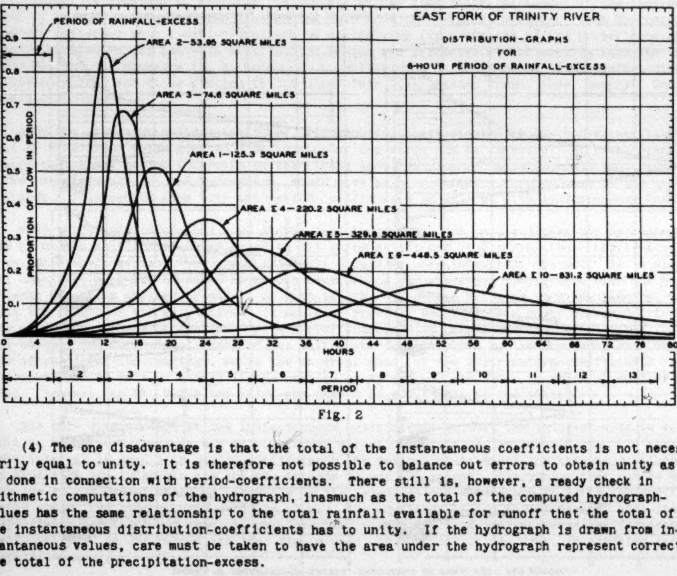


Fig. 2

(4) The one disadvantage is that the total of the instantaneous coefficients is not necessarily equal to unity. It is therefore not possible to balance out errors to obtain unity as is done in connection with period-coefficients. There still is, however, a ready check in arithmetic computations of the hydrograph, inasmuch as the total of the computed hydrograph-values has the same relationship to the total rainfall available for runoff that the total of the instantaneous distribution-coefficients has to unity. If the hydrograph is drawn from instantaneous values, care must be taken to have the area under the hydrograph represent correctly the total of the precipitation-excess.

The general conclusion is that, depending on convenience, either method may be used without sacrifice in the dependability of results.

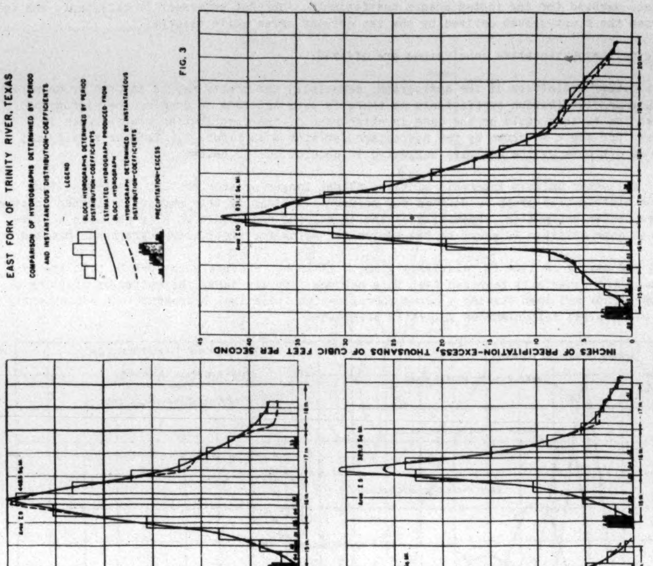


FIG. 3

Soil Conservation Service,
Washington, D. C.

DISCUSSION

WILLIAM T. COLLINS (U. S. Engineer Office, Huntington, West Virginia)--Mr. Smith's primary intent in this paper seems to be to introduce the instantaneous-coefficient method of runoff-distribution. His manner of presenting it, by comparison with the accepted standard procedure, enables all of us to evaluate the method for ourselves.

There is a matter of nomenclature that is worth noting. Mr. Smith uses the term "distribution-coefficients." This name should be given recognition since distribution of runoff is usually computed with coefficients, rather than actually with a "distribution-graph".

The question "How can an instantaneous flow be expressed as a per cent of the volume of excess precipitation?" is raised by this paper. Precipitation-excess is usually expressed in second-feet per time-length of the unit-storm and can be considered not as a volume, but as the average rate, for the interval, at which the precipitation was generated. When this definition is used a period-coefficient indicates, not that a certain portion of the volume passes the station in the period, but rather that the average rate of flow at the station during the period is that proportion of the average rate of generation. It is then consistent to express an instantaneous coefficient as a percentage since it means that the instantaneous flow was that per cent of the average rate of generation.

Morgan and Hullinghorst in their paper to which Mr. Smith refers give a procedure for deriving a hydrograph with any desired change in length of the basic storm. This method is based on the mass-curve of a hydrograph's ordinates, summed successively at times equal to the length of the storm. This curve, known as the S-curve, is the hydrograph as it would have occurred if the precipitation had continued indefinitely with a constant rate of runoff-generation equal to that of the storm. The hydrograph as it would have occurred with this same rate, but with a new storm-length, is obtained by shifting the S-curve on the time-scale the amount of the desired length of the unit-storm and then subtracting this from the original S-curve. This hydrograph is easily converted into a unit-hydrograph by multiplying its ordinates by the proper constant. A similar procedure for use with distribution-graphs was presented at the meeting last year by Laden, Reilly, and Minnotte [N. R. Laden, T. L. Reilly, and J. S. Minnotte, Hydrographs, distribution-graphs, and flood-routing in the upper Ohio River Basin, Trans. Amer. Geophys. Union, pp. 649-659, 1940].

With the unit-hydrograph established, distribution-coefficients for any convenient intervals, equal or otherwise, which give good definition of the curve can be computed. At first glance it appears that using medium intervals on the rising side, short ones near the crest, and long ones on the recession-side of the hydrograph, would give equal accuracy throughout and be the most efficient. This can be done with the period-coefficients as well as with instantaneous ones.

When it is considered that most storms last longer than one unit and that the hydrograph is made up by the addition of flows based on all parts of the set of distribution-coefficients, then it is immediately evident that equal intervals should be used throughout the set. It is also best that the intervals be equal to keep the mechanics of tabulation simple even when the coefficients are being applied to storms of unit-length. This does not mean that the interval must equal the length of the unit-storm. It would be possible and sometimes quite convenient in the case of flashy streams to use four- or six-hour intervals to define the hydrograph for a 12-hour unit-storm. The convenient length of the unit-storm is determined by the frequency and completeness of precipitation-readings, while the interval used for the distribution-coefficients is determined by the rate of change of the particular hydrograph and those to which it must be added. However, as Mr. Smith has said, one should be a multiple of the other.

The only disadvantage of the instantaneous coefficients is that the interval must be kept short so that the hydrograph may be considered essentially straight between points. If this same short interval is used with period-coefficients the period-values equal instantaneous values at the middle of the intervals and the two methods become equivalent. Everything that can be done with one in the way of changing intervals or the length of the unit-storm to which the coefficients apply, can also be done with the other. The advantage of the period-method, that its coefficients total 100 per cent, is not important. When deriving instantaneous coefficients their sum could be determined and that figure used, instead of 100 per cent, in checking later computations.

Instantaneous coefficients should be used because of the saving in labor for all streams with smooth regular hydrographs. It is not essential that one of the coefficients represent the crest of the unit-hydrograph because the time and height of the crest will be affected by the distribution of runoff generated in other intervals. A crest-coefficient is more desirable for very sharply crested unit-hydrographs.

A combination of the two methods is better for streams which have irregular or sharply crested hydrographs, where in order to define accurately the hydrograph it would be necessary to use excessively short intervals between the instantaneous coefficients. If a reasonably long interval is selected, and period coefficients with instantaneous coefficients at the dividing times are used, a good definition of the hydrograph can be obtained. If both the block-hydrographs and the instantaneous points are plotted first, drawing a line to represent the continuous values of an irregular hydrograph can be done more accurately.

The writer feels that instantaneous coefficients must actually be tried by interested hydrologists before their value becomes apparent. Preparation of this discussion required setting up conditions to which the method was applied. The clearer conception thus gained led to the conclusion that the method is to be preferred to the period-coefficient method but that a combination of the two is superior to either.

RUNOFF FROM TERRACED AREAS UNDER CONDITIONS OF EXTREME FLOOD

David W. Cardwell and W. E. Dickerson, Jr.
(Presented by David W. Cardwell)

The tropical hurricane that caused widespread destruction along the Georgia and South Carolina coasts in August, 1940, was followed by torrential rains over a broad area extending from northeast Georgia, through Tennessee and the Carolinas to northern Virginia. Meteorological aspects of this disturbance, rainfall-maps, and flood-data may be found in a special report published by the Tennessee Valley Authority [see 1 of "References" at end of paper]. In Virginia, the storm centered over the south-central portion of the State where rains of 10 to 16 inches occurred during the four-day period, August 14 to 17.

Located within this storm-area is the Danville Demonstration Project where the Hydrologic and Engineering Divisions of the Soil Conservation Service have been conducting runoff-studies on three small terraced watersheds since the summer of 1938. These watersheds are on cooperative farms where conservation-measures are being practiced. During this unusual storm-period, excellent records of rainfall and runoff were obtained. These records should prove valuable in studying the flood that followed this heavy storm.

The nature of this August rain was such that not only did the larger primary rivers rise to unprecedented flood-stages, but also many similar tributary streams left their banks to reach record heights. The magnitude of the flood-flows in various streams is indicated by stream-gaging records of the United States Geological Survey. Thirty-three of the Survey's gaging-stations in Virginia registered stages well above any previously recorded; eight of them had their water-level recorders overtopped by the flood-waters. These unprecedented floods occurred in the Roanoke and James River basins of south-central Virginia, and the New River Basin of southwestern Virginia. The flood of the New River was the result of excessive rains that began August 12 over the headwaters in North Carolina and moved downstream into Virginia. The path of the storm was unusual in that it followed the drainage-direction of each of these rivers. Floods of exceptionally rare occurrence also occurred in stream-systems of Tennessee and North Carolina.

The damage to agriculture, from the flood in the Roanoke River Basin alone, has been estimated at $3,116,238 in a preliminary report prepared by the Bureau of Agricultural Economics in cooperation with the county agricultural planning committees and State Agricultural Extension services of Virginia and North Carolina [2]. The Virginia State Highway Department lost 332 bridges during the flood, suffering an estimated damage of $860,000.

At the town of Chatham, a few miles from the runoff-studies, the Soil Conservation Service recording rain-gage showed nine inches of rain in the 24-hour period between 10 p.m., August 13, and 10 p.m., August 14. For this locality 7.1 inches is the 24-hour rain having a frequency of once in 100 years [3]. The maximum one-hour precipitation recorded by this gage was 2.7 inches between 3:20 p.m. and 4:20 p.m. on August 14. The above reference places this hourly rainfall at an occurrence of about a once in 25 years. This high intensity followed 4.3 inches that already had fallen and caused Cherrystone Creek, a small stream at Chatham, to rise approximately 18 feet above its normal stage, attain a width of 1,200 feet so that it flooded United States Highway 29 and State Highway 57, and inundated several small buildings on the outskirts of the town. By nightfall, August 14, all primary and secondary roads leading into Chatham were under water, and traffic was at a complete standstill until after midnight. Flooding of the power-supply caused disruption of service for several days. Conditions in Chatham were typical of many other central-Virginia communities.

During the storm and afterward, observations were made on various farms throughout the demonstration-project area. The most obvious serious damage to farms resulted from flooding of bottomlands along creeks and rivers. The fairly high rates of runoff sustained for a long period caused severe washing on unprotected slopes. Large amounts of rain falling on a thoroughly saturated soil served as severe tests of conservation-measures, but it was observed that wherever these measures had been properly maintained they were functioning satisfactorily. Clear water was seen to flow from fields covered with close-growing vegetation, whereas runoff from fields of tobacco and corn carried heavy loads of soil.

Records of runoff from the small watersheds employed in the runoff-studies on the Danville Project provide an insight into what was happening on the farms and fields draining into the flooded streams and rivers. There was considerable variation in the rates and total amounts of

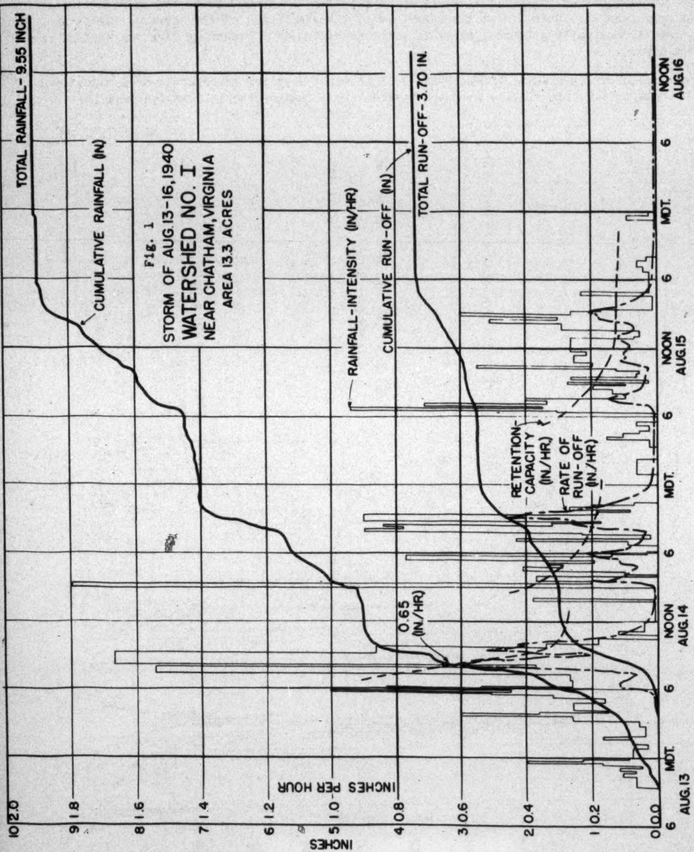


Fig. 1

STORM OF AUG.13-16,1940
WATERSHED NO. I
NEAR CHATHAM, VIRGINIA
AREA 13.3 ACRES

runoff from the three terraced areas near Chatham, due to dissimilar soils, terrace-systems, and other watershed-characteristics. The difference in total rainfall at the three locations, however, was reflected to a certain degree in the total runoff.

Large maps have been made showing in detail the watershed-characteristics and vegetal cover-conditions that account for the differences in runoff. In Tables 1 to 4 and discussion, an attempt is made to summarize the detailed information as to soil, topography, cover, and tillage for each of the watersheds. The watersheds are designated as W-I, W-II, and W-III. All three are terraced with channel-type terraces which carry runoff-water into outlet-channels above the runoff-measuring stations.

The ten terraces on Watershed W-I vary in length from 350 to 950 feet, the shortest being near the upper and the longest near the lower end of the area. All of the terraces lie to one side of the terrace outlet-channel, which is a thick meadow-strip occupying five per cent of the watershed-area.

The terrace outlet-channel of Watershed W-II contains a series of concrete drop-structures. It runs approximately from east to west and divides the drainage-area into two unequal parts.

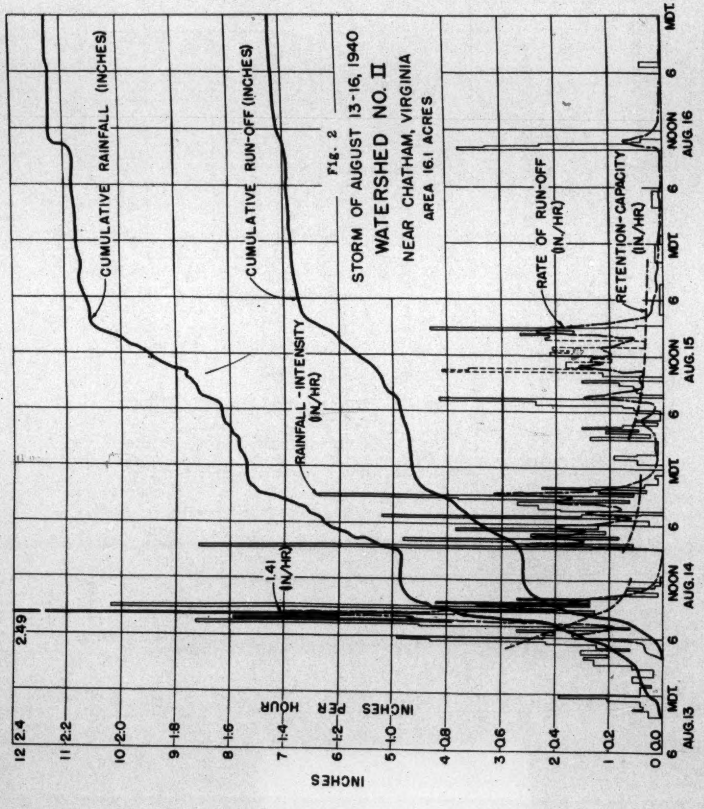


Fig. 2

STORM OF AUGUST 13-16, 1940
WATERSHED NO. II
NEAR CHATHAM, VIRGINIA
AREA 16.1 ACRES

The northern part, comprising about two-thirds of the drainage-area, is drained by ten terraces ranging in length from 450 to 810 feet. The remaining ten terraces draining the southern part range from 215 to 425 feet in length.

The outlet-channel on Watershed W-III divides into two branches a short distance above the runoff-measuring station. One of the branches is about four times as long as the other. Two of the 13 terraces lie between the two branches, each of these terraces draining in two directions toward both branches of the outlet. The longest terrace is 850 feet long; it lies near the upper edge of the area and drains into the main outlet at its upper end. The length of the remaining terraces range from 175 to 575 feet.

Typical cross-sections of terraces on each of the three watersheds show that their channels have an average area of nine square feet. None of the terraces were overtopped or broken through by runoff from the flood-producing rain.

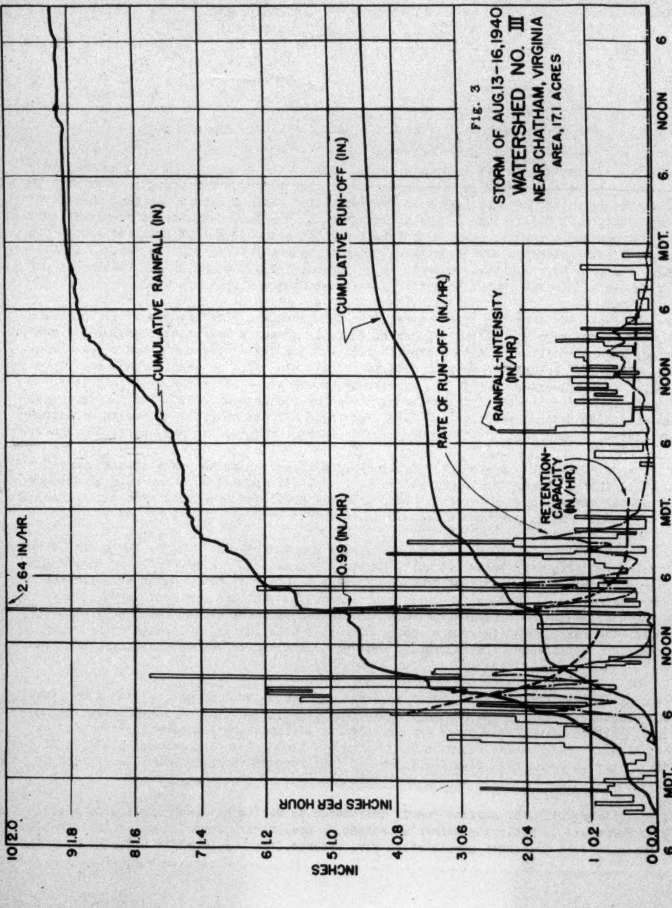


Fig. 3

STORM OF AUG.13-16,1940
WATERSHED NO. III
NEAR CHATHAM, VIRGINIA
AREA, 17.1 ACRES

Table 1--Permanent characteristics of watersheds

Watershed-characteristics	Watershed		
	W-I	W-II	W-III
Size, acres	13.3	16.1	17.1
Prevailing land slopes[a], per cent	7 and 12	5,6, and 8	4 and 7
Range in elevation[b], feet	590 to 670	600 to 655	595 to 625
Terraces, number	10	20	13
Length of terraces, feet	350 to 950	See text	See text
Overall grades of terrace-channels, inches per 100 feet	2	5	3-1/2
Soils			
Very fine sandy loam, per cent	75 (Madison)		
Clay-loam, per cent	25 (Louisa)	16 (Cecil and Wadesboro)	5 (Cecil)
Sandy loam, per cent	....	84 (Mayodan, Granville, and Appling)	89 (Appling, Durham, and Cecil)
Loam, per cent	....	....	6 (Seneca)

[a] Slopes on 30 per cent or more of the area. [b] Mean sea-level (approximate).

On W-I, the tobacco was in the extreme upper portion of the area and the corn on the lower end. The close-growing crops were in between on the steeper slopes. The crops on W-II were in small patches widely mixed. The portion north of the outlet-channel was in tobacco, wheat-stubble, and weeds, with the tobacco on the higher ground. The land nearest the runoff-measuring station was in peas and lespedeza. Weeds and wheat-stubble occupied all of the land south of the outlet-channel. The tobacco on W-III was being grown on moderate slopes in the central portion of the area. The peas were along the upper edge of the watershed and the wheat-stubble was on the lower side nearest to the runoff-measuring station where the slopes are steeper.

The rainfall-records from the gages operated on the three small watersheds were, in general, similar to that of the gage at Chatham. However, they all showed a lower total amount for the entire period, and intensities were consistently less. Since the flood-runoff had ended almost entirely by midnight of August 15, only records up to that time will be considered here. Throughout this period, the character of rainfall on watersheds W-I and W-III was almost identical. Somewhat larger amounts and intensities were registered by the gage on W-II. The rainfall- and runoff-data have been reduced to graphical form, showing: (1) The rainfall-intensity histogram; (2) the mass-curve of rainfall; (3) the hydrograph of runoff; and (4) the mass-curve of runoff.

It will be noted that the 24-hour rainfalls compare closely with the once-in-one-hundred years rain (7.10 inches) given for this locality [3]. On W-II and W-III, a low rate of seepage flow persisted for several days afterward. This flow was augmented by runoff from additional rains that followed, causing continuous flow for more than a week.

Short-time rainfall-intensities of this storm were not exceptionally high; for a considerable portion of the rain, they were below 0.5 inch per hour. Consequently, peak-rates of runoff did not exceed records obtained during some previous intense rainfall of short duration. However, instantaneous maximum rates of runoff were fairly high, with 0.63 inch per hour for W-I, 1.41 inches per hour for W-II, and 1.00 inch per hour for W-III. Because of the changeable nature of rainfall-intensities throughout the storm, rates of runoff continually fluctuated up and down and, consequently, appreciable rates of runoff were not sustained for periods greater than six hours.

In planning and designing flood-control measures, estimates must be made of rates of flow from various component parts of the drainage-basin. Applications of the unit-hydrograph or channel-storage methods for this purpose involve the use of "infiltration-capacity" values for various conditions. These values represent the rates at which water is absorbed by the soil. As yet, very little is known regarding variations of infiltration-capacity under conditions of extreme flood.

The infiltration-theory of surface-runoff introduced by Horton has been applied to small watersheds by Horner [4]. Employing Horner's methods, a preliminary computation of infiltration-capacities was made from the three graphs which give records from the Danville watersheds during

Table 2--Vegetal cover- and tillage-conditions at the time of flood

Watershed					
W-I		W-II		W-III	
Vegetal cover	Per cent of area	Vegetal cover	Per cent of area	Vegetal cover	Per cent of area
Korean lespedeza	50	Peas	9	Peas, thick growth	26
Meadow outlet	5	Common lespedeza	7	Grass and weeds in wheat-stubble	33
Woods	4	Weeds and wheat-stubble	67	Outlet-channel, grass	3
Corn, clean tilled	34	Outlet-channel, grass	2	Woods	7
Tobacco, very clean	7	Tobacco, very clean, one-third pulled	15	Tobacco, very clean, one-half pulled	31

Table 3--Comparison of rainfall and runoff on watersheds

Item	Watershed		
	W-I (13.3 acres)	W-II (16.1 acres)	W-III (17.1 acres)
Total rainfall to midnight August 15, inches	9.55	10.70	9.07
Total runoff attributed to above rain, inches	3.72	7.00	4.60
Percentage of rainfall occurring as runoff per cent	39	68	51
Greatest 24-hour rainfall (10:25 p.m., August 13, to 10:25 p.m., August 14), inches	6.95	7.66	7.04
Total runoff attributed to above rain, inches	2.75	4.75	3.45
Percentage of rainfall occurring as runoff per cent	40	62	49

Table 4--Highest average rates of runoff per hour for selected periods

	Size of watershed, acres	6-hour period, inches	12-hour period, inches	18-hour period, inches	24-hour period, inches
W-I	13.3	0.24	0.15	0.15	0.11
W-II	16.1	0.41	0.27	0.25	0.20
W-III	17.1	0.27	0.21	0.18	0.14

the flood-period. Since all three of the Danville watersheds have channel-type terraces, it is doubtful if the values obtained have any direct relationship to infiltration-capacity of the soil. Ponding of runoff-water in the terraces may have the effect of increasing infiltration-opportunity, both in time and amount. Nevertheless, the values obtained may be useful in making comparisons and in predicting the retentive ability of other similar watersheds under flood-conditions.

As a first step toward making the determinations, standard recession-curves were prepared for each watershed on the basis of hydrographs from previous storms where it was evident that no seepage-flow existed. These curves were used with the flood-graphs to separate seepage-flow from surface-runoff. Then, so-called infiltration-capacities were calculated for separable components of the hydrographs, balancing excess precipitation against runoff. Another set of values was obtained by disregarding reductions for seepage-flow. Reference will be made here to the latter figures only, because it is the total runoff including seepage-flow which contributes to floods. These might be more properly called "retention-capacities" than infiltration-capacities.

It appears that near the beginning of the storm, after initial retention had been accomplished (the second hydrograph-peak), "retention-capacity" on W-I was 0.64 inch per hour. It decreased to 0.25 inch per hour after the 24-hour maximum rainfall and, finally to 0.13 inch per hour toward the end of the runoff-period. Values of "retention-capacity" for W-II at the same points during the storm are 0.30, 0.10, and 0.07 inch per hour, respectively. For W-III, they are 0.46, 0.08, and 0.05 inch per hour. Values of apparent infiltration-capacity can be arrived at by adding the appropriate rates of seepage-flow to the figures just given. These rates of seepage-flow were found to range from 0.02 inch per hour to 0.07 inch per hour. It will be noted that in each case here represented, "retention-capacity" dropped rapidly during the first few hours, after which time only gradual reduction was evident. Even after nine to ten inches of rain had fallen each of these cultivated watersheds was able to hold back a small rate of flow. It is true that this rate was only in the range of 0.10 inch per hour, but even this may represent appreciable rates of stream-flow when applied to entire drainage-basins. Notice the relatively high "retention-capacity" of W-I, 0.25 inch per hour, after the first seven inches of rain had fallen.

Runoff from W-I was consistently lower than that from the other two areas, both in regard to maximum rates and total amount. This fact is reflected in higher "retention-capacity" values for all points throughout the flood-period. In addition, seepage-flow ended first on this watershed. Until more careful analyses of the data are possible, it will be inadvisable to attempt detailed explanations of these differences. It may be noted, however, that a splendid cover, principally lespedeza, existed on about 60 per cent of the W-I area.

References

[1] Floods of August 1940 in the Tennessee River Basin, Supplement to Precipitation in Tennessee River Basin, Tenn. Valley Authority Report No. 0-243-675, October, 1940.

[2] Roanoke River Watershed estimated agricultural flood damages, August 1940 Flood (preliminary), U. S. Dept. Agric. Bur. Agric. Economics in cooperation with county agricultural planning committees and State Agricultural Extension Services Virginia and North Carolina, Mimeo.

[3] David L. Yarnell, Rainfall intensity-frequency data, U. S. Dept. Agric. Misc. Pub. 204.

[4] W. W. Horner, The analysis of hydrologic data for small watersheds, U. S. Soil Conserv. Serv., TP-30, February, 1940.

U. S. Soil Conservation Service,
Virginia Agricultural Experiment Station,
Blacksburg, Virginia

LIMITATIONS OF THE DURATION-INTERVAL CONCEPT OF FLOOD-RECURRENCE INTERVALS

R. S. Goodridge

No manuscript or abstract of this paper, which was presented by title, was received.

U. S. Soil Conservation Service,
Washington, D. C.

SEPARATING STORM-HYDROGRAPHS FROM SMALL DRAINAGE-AREAS INTO SURFACE- AND SUBSURFACE-FLOW

C. R. Hursh and E. F. Brater
(Presented by C. R. Hursh)

Introduction--To evaluate the effects of different land-management practices on the water economy of small drainage-areas, it is essential that the stream-hydrograph obtained from small drainage-areas be separated into ground-water flow and the several components of storm-flow as accurately as the data permit. The difficulty of drawing a ground-water hydrograph for routine separation of complex storm-hydrographs has been specifically pointed out by numerous workers. For example, W. G. Hoyt [see 1 of "References" at end of paper] states that peaks occurring in such rapid succession that only rarely does surface-runoff have a chance to drain out "make the task of drawing a ground-water hydrograph difficult and the results uncertain." The improvement of present methods and the development of new methods for differentiating ground-water runoff and surface-runoff has been specifically pointed out as one of the deficiencies in hydrologic research [2].

Precipitation and other measurements essential to watershed-studies are being obtained from 30 small drainage-areas supporting continuous stream-flow and ranging in size from three square miles down to 20 acres. These drainages lie within the Coweeta Experimental Forest, an area devoted to forestry-research in the high rainfall-belt of the Southern Appalachian mountains in Macon County, western North Carolina. The mean annual precipitation of 70 inches is well distributed throughout the year. About 50 storm-hydrographs are obtained within a single year for each stream.

Description of experimental drainage-area--For the purpose of discussing some of the results of this study, records from a drainage-area of 40 acres will be used. This drainage, No. 13 on the Coweeta Experimental Forest, is a forested watershed with continuous stream-flow from pervious soils overlying a deeply weathered country rock. Discharge was measured with a right-angled V-notch weir. The lowest elevation of the area is 2,350 feet whereas the highest portion has an elevation of 3,000 feet. The water-yields from this area have been found to be quite similar to the yields of larger drainage-basins in the region.

The mean runoff expressed as cubic feet per second per square mile for this drainage for the period of April, 1936, to January, 1941, is 2.38 csm. The seasonal means are as follows: November, December, January, 2.02 csm; February, March, April, 4.10 csm; May, June, July, 2.09 csm; August, September, October, 1.61 csm.

Methods: General discussion--Analysis of a large number of storm-hydrographs calls for the use of routine practice which may be carried out with a minimum of additional replotting of the original record. It is to determine a satisfactory procedure for routine hydrograph-analysis that a special study has been made of the problems relative to ground-water separation.

As a preliminary to separating ground-water during storms, a normal depletion-curve is prepared for each drainage-area using storm recession-curves. The depletion-curve is then converted to read directly in gage-height over the weir and adjusted to the time-scale of the original field-chart. This adjusted curve is then transferred to transparent cloth and used as an overlay on the original record. Many research-problems appear in the preparation and use of curves of normal stream-depletion which will not be considered in the present discussion. It was found that for practical purposes a composite curve could be used without taking into account seasonal and annual differences. Such differences, although present, were not great enough to be significant within the mechanical errors of drafting the base-curve.

Surface storm-runoff as overland-flow has not been observed on this drainage-area; nevertheless, characteristic flood-hydrographs are produced by heavy rains. A simple hydrograph, such as Figure 1, is produced by an intense summer storm of 0.69 inches falling within a period of 30 minutes and equivalent to an intensity of 0.80 inch per hour for the entire storm. Intensities for the maximum five-minute interval amounted to 1.68 inches per hour and for the maximum ten-minute interval 1.56 inches per hour. The volume of storm-flow discharged as indicated by the area above the base-line 3, Figure 1, is computed to be 1,141 cubic feet. Base-line 3 in this case is merely one of three straight lines drawn from an arbitrary point on the normal recession-curve to points (point a, Fig. 1) on the hydrograph approximately two, three, and four hours after cessation of rainfall.

Measurement of channel-area--The length of the stream-bed for the drainage is 4,006 feet and the average width is 5.2 feet. These dimensions include only the gravelly stream-bed and not the

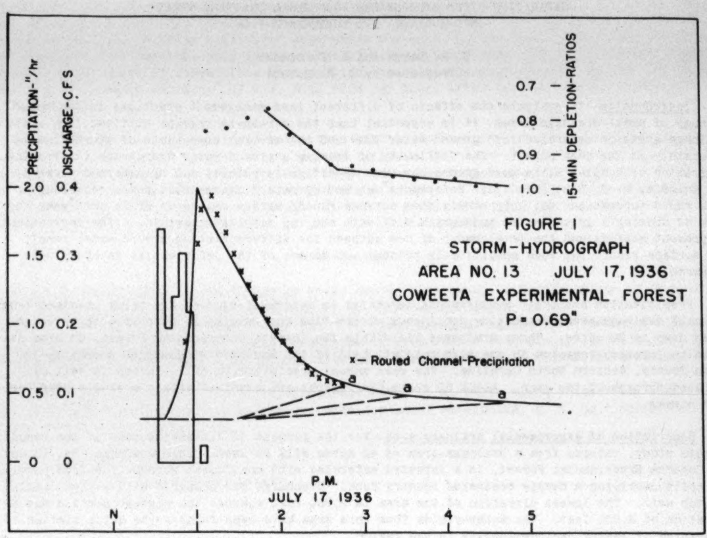


FIGURE I
STORM-HYDROGRAPH
AREA NO. 13 JULY 17, 1936
COWEETA EXPERIMENTAL FOREST
P = 0.69"

steep heavily vegetated banks of the stream. Channel-precipitation is computed from the area of the stream-bed after making an allowance for vegetative interception, at five per cent. Using this deduction for the 0.69-inch storm producing the hydrograph shown in Figure 1, channel-precipitation is computed to be 1,138 cubic feet. As this amount is practically the same as the total discharge for the storm, it is apparent that the entire discharge above base No. 3, Figure 1, can be accounted for as channel-precipitation. Other types of storm-flow make up only a very small portion of the hydrograph.

It is believed that the importance of channel-precipitation as a component of the flood-hydrograph has not been fully appreciated. Many hydrographs similar to the one above, where practically the entire hydrograph results from channel-precipitation, have been observed on the Coweeta streams. It is possible that this factor should be more fully accounted for even in the case of much larger streams.

Storage-discharge relationship--A storage-discharge relationship may also be employed to demonstrate that the hydrograph shown in Figure 1 comes largely from channel-precipitation. If the correct separation of surface-runoff has been made by base-line 3 in Figure 1, that portion of the hydrograph above this line should be entirely the result of channel-precipitation. Therefore, the depletion of this quantity, after the end of rainfall, is simply the natural draining off of the accumulated channel-storage. Under these conditions there exists a relationship between the quantity of channel-storage (S) present at any instant and the rate of discharge (Q) occurring at that instant. This principle was utilized by Horton [3] to derive hydrographs of overland-flow from stream-flow hydrographs. The storage-discharge relationship is derived from the recession-side of the graph beyond the point of contraflexure. The procedure is as follows: Increments of discharge are added accumulatively, working from right to left, starting at the point where the separation-line meets the recession-curve (point a, Fig. 1). When any particular discharge-increment is added the accumulated quantity represents the amount of channel-storage present at the beginning of that increment. The rate of discharge occurring at that time may be related to the corresponding value of storage. A set of points derived in this manner will represent the relationship between channel-storage and discharge only if the line of separation is drawn so that very nearly all the discharge above the line is a result of channel-storage. If, for instance, the derivation of these points is carried up beyond the point of contraflexure, where the channel-storage is being augmented by channel-inflow or in this case precipitation on the channel, the plotted points immediately fell away from the trend of the lower points. It could be expected, therefore, that a similar distortion of the storage-discharge relationship would occur if the lines of separation were drawn in such a manner that some ground-water discharge is included in the area above the line. This was found to be the case.

Test of trial base-lines of direct runoff--Therefore, the derivation of this relationship was utilized as a test to determine the correctness of a given line of separation. The procedure is illustrated for the hydrograph of Figure 1, where three different base-lines were tried. The storage-discharge relationships derived for all three sets of lines are shown by points plotted on Figure 2. It may be seen that the points determined from base-line No. 3 plot in a consistent curve whereas the others do not. If these points are plotted logarithmically it is found that only the series derived from base-line No. 3 fall on an approximate straight line. It is concluded therefore that the third base-line provides about the correct separation.

Routing channel-precipitation--It is believed that the exactly correct line of separation would be a smooth reverse curve rather than a straight line or a series of straight lines. This point has been more completely discussed in a previous paper [4]. The results of this study serve to strengthen the belief. More recent studies of changes in the water-table of index-wells during heavy storms have indicated that a curved line more nearly represents the actual fact.

The same procedure was applied to four other hydrographs with similar results. The series of points derived from each of the five hydrographs were plotted together logarithmically and were found to produce a consistent relationship. The solid line shown in Figure 2 was derived from a straight line drawn through these five series of points. If this line represents a reasonably correct relationship between channel-storage and discharge it should be possible to route channel-precipitation through the channel and completely reproduce those hydrographs produced entirely by channel-precipitation. The hydrograph shown in Figure 1 was reproduced in this manner, utilizing the diagram of channel-precipitation shown on the Figure. The results of the reproduction are shown by the small x marks. The points are obtained by applying the storage-equation in conjunction with the storage-discharge relationship to successive time-increments.

The storage-equation in its fundamental form is as follows

$$S_1 + P_{ch} - Q = S_2$$

where S_1 = channel-storage at the beginning of a time-interval, S_2 = channel-storage at the end

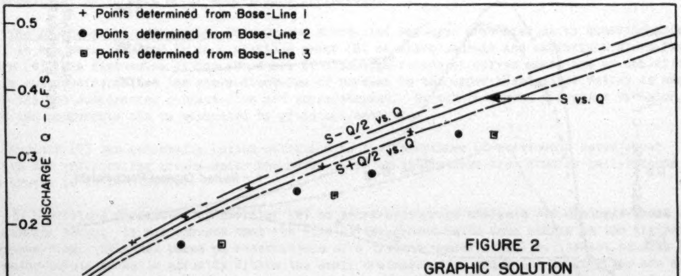


FIGURE 2
GRAPHIC SOLUTION
OF
CHANNEL-STORAGE EQUATION
AREA NO. 13
COWEETA EXPERIMENTAL FOREST

of a time-interval, P_{ch} = increment of channel-precipitation during interval, and Q = average rate of outflow during interval.

If a sufficiently short time-interval is selected it may be assumed that $Q = (Q_1 + Q_2)/2$, where Q_1 and Q_2 are the rates of discharge at the beginning and end, respectively, of a time-interval. The equation may then be rearranged into the following form

$$(S_1 - Q_1/2) + P_{ch} = (S_2 + Q_2/2)$$

The use of the storage-equation in this form to permit a graphical solution was first brought to the writers' attention by C. O. Wisler, Professor of Hydraulic Engineering, University of Michigan.

Graphic solution for routing channel-precipitation--In this form the solution may be accomplished graphically by utilizing the auxiliary curves shown in Figure 2. Knowing the rate of discharge of the beginning of any interval, the amount of P_{ch} occurring during that interval is added to the particular abscissa of the (S - Q/2)-curve which corresponds to that discharge. The abscissa equal to $(S - Q/2 + P_{ch})$ is thus obtained. Vertically above or below this point will be found a point on the (S + Q/2)-curve which indicates the rate of discharge at the end of the interval. This procedure may be quickly carried through for successive intervals. The length of interval was taken as five minutes in this case. It is obvious that care must be taken to keep all the elements of the storage-equation in the same units. It will be noted that the points obtained, Figure 1, give a fairly good reproduction, even for the rising side of the hydrograph. This would seem to be a further indication that the storage-discharge relationship is the correct one and that the graph in this case is chiefly the result of channel-precipitation.

Tests for subsurface storm-flow--It would make little practical difference whether base-line 1, 2, or 3 were selected in the hydrograph of Figure 1, since the amount of discharge above the base-line would not vary by a significant amount considering the accuracy of hydrologic observations. However, the chief purpose of studying such simple graphs is the derivation of information which may aid in the solution of more complex cases. Such a case is the hydrograph shown in Figure 3 resulting from a continuous long rain. The hydrographs shown in both Figures 3 and 1 are midsummer storms. The rainfall-intensities that produced the hydrograph on Figure 3 are not nearly so intense as those producing the hydrograph in Figure 1. Since it has been demon-

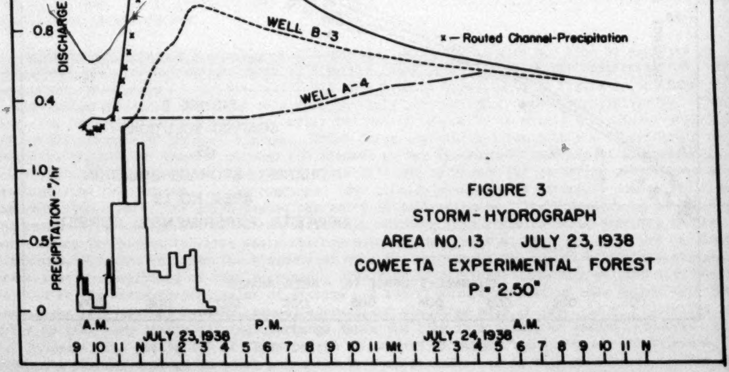


FIGURE 3
STORM-HYDROGRAPH
AREA NO. 13 JULY 23, 1938
COWEETA EXPERIMENTAL FOREST
P = 2.50"

strated that no direct overland storm-flow occurred in the storm of Figure 1, it would follow that precipitation-intensity could not have been great enough to exceed infiltration-rates for the storm of Figure 3. Consequently, on this basis of reasoning, no part of the hydrograph in Figure 3 could have resulted from direct runoff other than channel-precipitation. Evidence to substantiate this belief is obtained by using still other criteria to facilitate the separation of the storm-hydrograph. One of these is the use of the unit-hydrograph or distribution-graph. Another is the use of depletion-ratios. Still another is the observation of changes in the water-table of index-wells.

The hydrograph in Figure 3 is unlike the hydrograph in Figure 1 in that channel-precipitation accounts for only a minor portion of the total flow. This was shown by routing the channel-precipitation through as was done in Figure 1. In this case the points are plotted downward from the actual hydrograph with the intention of establishing the approximate location of the base-line. The time-element involved in locating these points may be somewhat in error. That is, the location of the group of points as a whole could reasonably be shifted to right or left through an increment of a few minutes. However, the quantity of water represented by the area above the points accounts for all the channel-precipitation while all that below the points appears to have resulted from underground storm-flow or ground-water flow.

Use of the unit-hydrograph--The approximate correctness of the line of separation of channel-precipitation in Figure 3 is further substantiated by the use of the unit-hydrograph or distribution-graph. The base-length of the distribution-graph for this drainage-area is about two hours and ten minutes. Effective rainfall ends at about 2:50 P.M. Therefore, according to the distribution-graph, all channel-storage derived from channel-precipitation must have passed the gaging-station by about 5 P.M. This agrees approximately with the results as obtained by routing channel-precipitation.

Use of depletion-ratios--When the discharge depletion-ratios of the recession-side of the hydrograph in Figure 3 are determined by half-hour periods, it is found that at no point is the ratio less than 0.92. (This ratio is obtained by dividing the rate of discharge at any instant by the rate occurring one-half hour earlier. Any other interval could be chosen.) The value for the ordinary dry-weather depletion-curve of discharge for this stream is about 0.9996. For several days following a rain the depletion-ratio varies from 0.92 to 0.99. Depletion-rates for direct runoff known to be of surface-origin are 0.88 or less. In no other part of the several years of records obtained on this stream does the ratio become less than 0.92. The fact that at no point on the recession-curve shown in Figure 3 is the depletion-ratio less than 0.92 may be considered as further evidence that the discharge shown in the hydrograph below the base of channel-precipitation is made up of underground storm-flow.

The ground-water hydrograph--Underground storm-flow has been commented on by numerous writers. It has been referred to in a previous paper [5] as storm-seepage and subsurface storm-flow. Barnes [6] in a discussion of the structure of discharge-recession curves makes use of depletion-ratios and considers that the storm-discharge of streams in the upper Mississippi Valley is made up of the two components, surface-flow and storm-seepage. He has indicated a process by which these two components can be separated by graphical analysis.

Meinzer [7] has repeatedly called attention to the importance of continuous water-level records for interpreting ground-water phenomena. For small drainage-area studies well-records have proven to be invaluable.

In a previous discussion by Hertzler [8] on storm-hydrograph analysis for drainage-areas on the Coweeta Forest, it was assumed that the rise of the ground-water base starts at the beginning of stream-rise. This was based on observations of a limited number of wells. Recent studies of the water-levels of wells actually within the small drainages from which the hydrographs are obtained now indicate that there may be a delay of several hours before a significant rise of ground-water occurs.

So far as storm-water may actually become part of an established water-table, it may also be considered as storm-augmented ground-water. The rapid percolation from this water could then be called augmented ground-water discharge during storm-periods. It is differentiated from recognized ground-water discharge only by its faster percolation-rates or by the time of its reappearance in the stream-channel.

Obviously the underground storm-flow contributing to the lower portion of the recession-side of the storm-hydrograph has more nearly the characteristics of true ground-water, whereas that contributing to the upper portion has more nearly the characteristics of channel-interception.

Use of well-records--Well-records also give an indication as to the nature of the water making up the major portion of the hydrograph shown in Figure 3. Changes in the height of the water-level of two Coweeta Forest wells, but not situated on the drainage-area No. 13, are shown in the same time-scale on the storm-hydrograph. It is apparent that there are different types of rises shown by the two wells. By a study of previous storms Well A-4 is known to rise slowly and to fall slowly and to tend to follow the seasonal depletion-curve of the stream-hydrograph. At the end of the time-period shown in Figure 3, it is still rising and will eventually meet the curve of normal stream-depletion. Such a well appears to be more closely associated with normal stream depletion than with the storm-hydrograph. Well B-3 tends to follow the storm-hydrograph much more closely. The shape of the other well-hydrographs for this storm ranges from low rises similar to Well A-4 to even more rapid rises than Well B-3 but similar to it. Apparently, the hydrograph below the separation-line of channel-precipitation is built up from storm-water temporarily stored along water-tables in close enough proximity to the stream to contribute a significant amount of percolated water during the period of the storm. Whether or not a portion of this water should be called ground-water discharge is apparently a question of definition.

What has been most lacking is an explanation of the nature of underground storm-flow and some proof that it can be related to measurable ground-water phenomena. An explanation has been sought in the changes of water-levels of selected wells. These wells are selected with regard to topography, soil-profile, and proximity to the stream.

Wells to be used for indicators of this separation must have been studied for a sufficient length of time to standardize their performance against the stream. For example, those wells known to fluctuate in keeping with seasonal depletion of the stream are probably the ones that indicate significant water-rises of seasonal ground-water stores. Such a well is indicated by A-4 in Figure 3. Those wells that rise rapidly and produce hydrographs similar to Well B-3 in Figure 3 are the ones that indicate the position of important water-tables contributing to subsurface storm-flow during the storm-period. Consequently, with a previously determined knowledge of the behavior of a particular well in relation to the stream-hydrograph, it is possible to use the well-hydrograph for the separation of storm-augmented ground-water flow.

A possible explanation of the behavior of different wells lies in their relative position with regard to topography and proximity to the surface-stream. The Well J-1, Figure 4, has a water-level ranging from six to nine feet below the ground-surface. It is on drainage-area No.

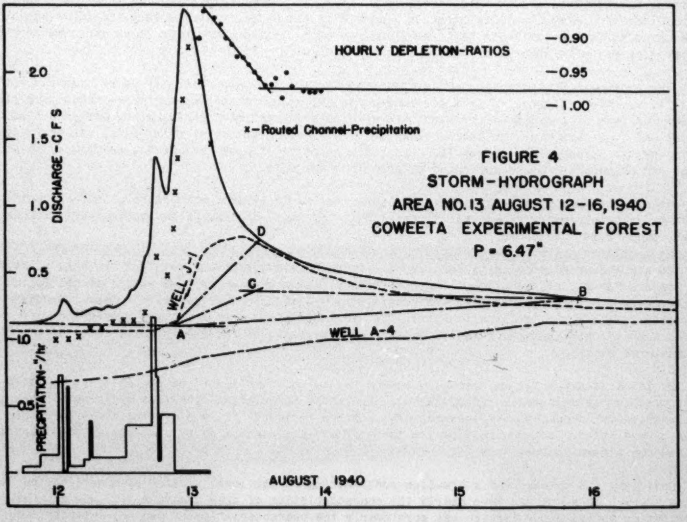


FIGURE 4
STORM-HYDROGRAPH
AREA NO. 13 AUGUST 12-16, 1940
COWEETA EXPERIMENTAL FOREST
P = 6.47"

13 in a narrow but rounded-bottom ravine with moderately steep slopes. The well is about 200 feet from the stream. The soil-profile at the well is porous, colluvial or frost-creep material. Consequently, the soil-profile in which it is located allows the rapid passage of water both vertically and laterally. Ravines filled with such colluvial material may have buried stream-lines that were established before the filling in with the colluvial material and along which water may find an opportunity for rapid movement. The Well J-1, Figure 4, offers ample evidence that there is a rapid rise of an established water-table during moderately heavy storms. Well A-4, not on drainage-area No. 13, has a water-level ranging from nine to 12 feet below the surface and is situated on sloping benchland about 600 feet from the stream.

In the storm shown in Figure 4, and in numerous other storms that have been studied, there appears to be a time coincidence between the maximum height of the water-level in Well J-1 and the sharp break in the depletion-ratios on the recession-side of the hydrograph. This break is believed to be the significant reference-point for drawing in the ground-water hydrograph. At this point, the forms of storm-water most nearly approaching channel-precipitation have passed the gaging-station. The recession-hydrograph shows depletion-ratios in the magnitude of normal ground-water depletion. It is reasonable to believe that the stream is now receiving normal ground-water from higher water-table levels resulting from the storm. The general shape of the hydrograph of Well J-1 suggests that the falling of the water-level of the well tends to follow the shape of the recession of stream-discharges. The fact that the water-level of the Well J-1 falls rapidly indicates that ground-water percolation from certain portions of the drainage-area may be reaching the stream at a relatively rapid rate during the storm-hydrograph.

Hydraulic significance of rise in the water-table--It is recognized that many types of ground-water may contribute to storm-flow. One rough classification of these types might distinguish between that water which actually reaches the water-table and that which does not. The hydrograph shown in Figure 3 is largely of the former type. The cause of this sudden increase in ground-water (gravity-water) discharge may be explained by considering the hydraulics of percolation along with the evidence of changes in the elevation of the water-table as shown by well-records. Two of the more important variables which might affect the discharge are the cross-sectional area through which the water may enter the stream and the slope of the water-table at the stream-edge. Since these steep mountain streams tend to rise very little during a storm, the change in cross-sectional area is not a major factor. However, it is possible that the slope of the water-table at the stream-edge may increase considerably during the storm-period. If, for instance, the slope changed from one in 20 to one in five during the storm, the discharge would be four times as great if flow is laminar or twice as great if flow is turbulent. The evidence indicates that a much greater change than this might occur at the stream-edge where during a long rain the water-table may actually follow the ground-surface for a short distance on each side of the stream. It should be emphasized that it is the slope directly at the water's edge which controls the contribution to the stream. It is quite possible that at some distance from the stream the water-table might temporarily slope away from the stream, but this would have no immediate effect on the rate at which ground-water enters the stream.

Applications and conclusions--For routine practice the sharp break of the recession-hydrograph is used as a reference for a new maximum on the normal depletion-curve extended under the hydrograph from the right. As a rule the location of this break may be quickly found by plotting a few recession-ratios of discharge above normal depletion by half-hour intervals. The actual ratios are not so essential but the trend of the plotted points is an aid to the eye in locating a major break in the recession-curve. In practice this is done quickly on the original chart and kept as a permanent record.

This plotting procedure alone may be used to locate the point of rise of ground-water to a new discharge-level for simple storms without reference to the well-hydrograph. For compound storms where there is a masking of the recession for any precipitation-period by a second rise, the index-well peak can be substituted for the plotted depletion-ratios. In any case the index-well peak may be used as a check on the location of the point in question should it be difficult to locate by other methods. On some storm-hydrographs this point may be located through inspection for practical purposes without further check.

The point A in Figure 4 is located on the normal depletion-curve from the left a time-distance indicated by the beginning of the rise in the water-level of Well J-1, or any other similar well having a storm-peak that coincides with the maximum break on the stream-recession hydrograph. Three lines might then reasonably be drawn for the base of the ground-water hydrograph, A-B, A-C, and A-D.

For the Drainage-Area No. 13 on the Coweeta Forest, it would be logical to draw in the base of ground-water to appear quite similar to the shape of the hydrograph of Well J-1. In practice a straight line is actually used on the head chart because this can be drawn in more easily than a curved line. The difference between the curved line and the straight line in reading the head chart would not be important. This base for ground-water is shown as line A-D, Figure 4. The discharge below this base may be viewed as storm-water that has reached the stream as storm-augmented percolation of gravity-water. The discharge between this base and the base of channel-precipitation may be viewed as rapid seepage through unsaturated soil-profiles, or as coming from naturally wet areas closely associated to the surface-stream.

By applying such procedures as have been discussed it is believed to be possible to obtain a greater degree of uniformity in the routine separation of subsurface-flow in storm-hydrographs than could be obtained by inspection alone.

A complete explanation of storm-seepage on the drainage-area under discussion must await further studies of water-tables under additional conditions of soil-topography. In the light of the present information on the subject, the storm-hydrograph such as is shown in Figure 4 from Drainage-Area No. 13, appears to be made up of storm-water from the following sources, arranged approximately in the order in which they may contribute to the storm hydrograph:

(1) Channel-precipitation.

(2) Contributions from areas of normally shallow water-tables located in close proximity to the stream, and occurring in soil-profiles which are quickly saturated. Where such conditions occur along a stream, it is expected that there will be an actual increase in the width of the channel and subsequent increase in the amount of channel-precipitation. Areas of high water-tables adjacent to spring-heads would be expected to contribute similarly.

(3) Storm-water moving through layers of porous soil-material close to the surface and under considerable gradient and reaching the stream during the period of the storm-hydrograph. Frequently, such layers overlie those that are much less porous, as for example, is the case between A- and B-horizons of many soil-profiles.

(4) Storm-seepage from large bodies of colluvial or other porous soil-material that has filled in along stream-banks. Storm-seepage along natural subterranean drainage-lines that exist in filled ravines and valleys.

(5) Storm-seepage as a result of actually piling up of a high water-table in talus-slopes in close feeding relation to the surface-stream. These talus-slopes are fed by relatively rapid seepage or percolation from steep slopes. The depletion of this temporarily stored storm-water in relatively porous material may account for the recession-side of the hydrograph until its approach to normal depletion-rates.

It is conceivable that all the forms of storm-water mentioned above may contribute to the hydrograph in some orderly fashion related to time. On drainages of uniform topography and soil-mantle this time-factor may become a valuable tool for the study of storm-water. On less uniform drainage-areas any regular appearance of the different types of storm-water into the stream will be more difficult to observe.

References

[1] W. G. Hoyt and others, U. S. Geol. Surv. W.-S. Paper 772, 1936.
[2] National Resources Planning Board, Deficiencies in hydrologic research, 1940.
[3] R. E. Horton, Publication 101, Horton Hydrologic Laboratory, 1935.
[4] E. F. Brater, Trans. Amer. Soc. Civ. Eng., v. 105, pp. 1154-1192, 1940.
[5] C. R. Hursh, Trans. Amer. Geophys. Union, Part II, pp. 301-302, 1936.
[6] B. S. Barnes, Trans. Amer. Geophys. Union, Part IV, pp. 721-725, 1939.
[7] O. E. Meinzer, Trans. Amer. Geophys. Union, pp. 36-37, 1933.
[8] R. A. Hertzler, Civ. Eng., v. 9, pp. 487-489, 1939.

U. S. Forest Service, Appalachian Forest Experiment Station,
Asheville, North Carolina

DISCUSSION

W. G. HOYT (U. S. Geological Survey, Washington, D. C.)--It is with considerable pleasure that I discuss the paper by Messrs. Hursh and Brater entitled "Separating storm-hydrographs from small drainage-areas into surface- and subsurface-flow". The paper marks a distinct advance in our knowledge of what we may call the stream-flow cycles in drainage-basins of significant size in contrast or as a complementary part of the surface- or overland-flow cycle. By this I do not mean that we still do not have a long way to go. The authors have, however, presented some definite factual information concerning the magnitude of subsurface storm-flow. With respect to the surface-runoff phenomena we are deeply indebted to many who, based on the large amount of data collected at experimental areas during recent years, have developed sound, rational concepts of surface runoff as such. Others have developed rational theories and concepts relating more specifically to the movement of water after it has reached river-channels. Still others have struggled with the complexities involved in what is so apparent, namely, the rapid transition of rainfall into flood-flows in areas where apparently there is little, if any, surface- or overland-runoff. It is this phenomenon which Messrs. Hursh and Brater have so clearly described in so far as certain areas in the Coweeta Experimental Forest are concerned. They give quantitative expression to a phenomenon that many have felt for some time has a distinct bearing on flood-flows as such. In general, I believe up to within a relatively few years ago hydrologists looked upon water in the ground mostly with respect to a more or less static water-table, its rise and fall. Hydrograph-analyses such as made by Messrs. Hursh and Brater in conjunction with the results of experimental data indicate that there is a dynamic phase of ground-water flow associated with floods. This dynamic phase is of considerable significance in present problems and is a phenomenon about which we have much to learn. It is in the study of this phenomenon that students of ground-water can be especially helpful.

The facts presented by Messrs. Hursh and Brater seem to indicate, to me at least, the possibility, as Mr. Snyder pointed out in 1939, and also as discussed at the round-table held last year, that it may be necessary when considering stream-flow as such to consider the division of rainfall into surface-runoff and ground-water runoff to take place both on and below the soil-surface instead of entirely above the surface. In other words, in so far as direct flood-runoff in contrast to surface-runoff is concerned, may not many of our phenomena relating to surface-detention, net rainfall-excess, and infiltration relate not only to the surface of the ground but to an indeterminate zone lying at and extending a considerable distance below the ground-surface? In developing such a concept I do not believe we would be in any way retrogressing in our thinking but rather believe we would be taking a step forward with respect to our knowledge of stream-flow from drainage-basins of significant size.

PRELIMINARY RESULTS OF RUNOFF-STUDIES AT FENNIMORE, WISCONSIN, SHOW LOW RATES AND AMOUNTS OF RUNOFF

N. E. Minshall
(Presented by title)

To secure runoff-data applicable to the "Upper Mississippi Valley Upland Areas", runoff-, rainfall-, and temperature-measuring stations were established in June, 1938, on four small watersheds within the Fennimore (Wisconsin) Demonstration Area of the Soil Conservation Service. The studies are conducted by the Hydrologic and Engineering Divisions of the Service.

The four watersheds, designated W-I, W-II, W-III, and W-IV, are one mile north of the city of Fennimore. The characteristics of each watershed have been carefully determined by field-surveys and were compiled on topographic, soil, and cover- and tillage-maps, prints of which are available. Table 1 summarizes the permanent characteristics of the Fennimore watersheds as shown on these detailed maps.

Drainage-density in Table 1 expresses numerically the degree of dissection of each of the watersheds. The "form-factor (A/L^2)" serves to indicate the shape of the drainage-area. A large form-factor indicates a broad or fan-shaped area such as W-II, the smaller value for W-III indicates a drainage-area the length of which is greater than its average width.

Watershed W-I includes the entire area of the other three and an additional 83 acres. This watershed has a maximum length of one mile and an average width of one-half mile. Impervious areas within this watershed consist of a black-top road and a gravel-road, and three sets of farm buildings, all of which occupy four per cent of the area.

Watershed W-II is a fan-shaped area having no well-defined drainage-way. There are no impervious areas in this watershed.

The length of Watershed W-III is approximately twice its average width. One set of farm buildings and a gravel-road constitute the total impervious area of three per cent. There is little evidence of gullying, although the area has a well-defined drainage-system.

Table 1--Characteristics of Fennimore watersheds

Watershed-characteristics	Watershed			
	W-I	W-II	W-III	W-IV
Size, acres	330	22.8	52.5	171
Range in elevation,[a] feet	1,105 to 1,247	1,158 to 1,212	1,124 to 1,211	1,146 to 1,247
Prevailing land-slopes,[b] per cent	4 and 8	4 and 8	4 and 10	4 and 7
Length of principal waterway, feet	5,200	400	2,200	2,450
Range in land-slopes, feet	1 to 20	1 to 10	2 to 20	1 to 12
Average slope of principal waterway, per cent	1.8	5.0	3.5	2.2
Total number of waterways	6	2	2	4
Drainage-density,[c] feet per acre	33	32.8	44	49
Form-factor (A/L^2)[d]	0.54	1.1	0.46	0.78
Soils				
Tama silt-loam, per cent of area	52	77	43	66
Dubuque silt-loam, per cent of area	40	18	53	27
Genesse-complex silt-loam, per cent of area	8	5	4	7

[a] Approximate elevations above mean sea-level. [b] Slopes existing on 30 per cent or more of the area. [c] Total length of waterways in feet divided by the number of acres. [d] Area of watershed in square feet divided by the square of the length of the watershed (not of the principal waterway) in feet.

Watershed W-IV is the westerly half of Watershed W-I and is similar in shape to W-II although it has a more clearly defined drainage-system. Impervious areas amount to four per cent and consist of the black-top road and one set of farm buildings.

The few waterways on the four watersheds are generally broad and are well-protected by vegetation. The exceptionally heavy growth in the lower third of the principal waterway on W-III proved quite effective in retarding and reducing runoff.

The soils on all four watersheds are silt-loams, with Tama and Dubuque predominating. The depth to impervious or impeding strata exceeds 48 inches over the greater portions of W-I, W-II, and W-IV. On W-III, with 53 per cent Dubuque silt-loam, this is true only for about one-half of the area, the depth in the other half averages about 36 inches.

The three years of the records thus far obtained are hardly sufficient to use as a basis of definite recommendations for the design of conservation-structures, nor can definite quantitative conclusion be drawn as to the effect on runoff of various factors, such as shape, slopes, cover, and soils. However, these records show rather definitely that, with the soils and the type of vegetal cover and tillage existing on these watersheds, the rates and amounts of runoff are quite low. The first indication of this became apparent shortly after the installations were completed. During a two-week period in September 1938 a total of 10.65 inches of rain was recorded on these watersheds, of which ten inches were retained and only 0.65 inch ran off. As the rainfall-intensities for short duration were comparatively low it remained for later records to verify this first indication. Only rains of ordinary intensities occurred during the first two years and runoff from them was quite small. It was not until the summer of 1940 that rains of high intensity were experienced.

Short intense rains, causing only small amounts of runoff, occurred on successive days in June, 1940. The first of these rains, on June 6, amounting to 0.82 inch in 15 minutes (average intensity of 3.3 inches per hour), produced only 0.01 inch of runoff. Another on June 8, an 0.60-inch rainfall in eight minutes (average intensity of 4.5 inches per hour), caused only 0.03 inch of runoff.

Five inches of rain fell between 4:45 p.m., July 25, and 4:45 p.m., July 26, 1940; nearly three inches of this amount occurred in one and one-half hours near the end of the storm. The maximum intensities for various durations during this storm, and their estimated frequencies based on data given in United States Department of Agriculture Miscellaneous Publication 204 are as follows:

Rainfall-intensity, inches per hour	Duration, minutes	Estimated frequency, years
5.9	5	5
4.3	10	Between 2 and 5
3.4	15	Nearly 2
3.3	30	10
2.3	60	25

A partial record of this rain and the resulting runoff is given in Table 2.

Table 2--Rainfall- and runoff-data for storm of July 25-26, 1940

Item	Watershed and area in acres			
	W-I, 330	W-II, 22.8	W-III, 52.5	W-IV, 171
(1) Total rainfall, inches	5.11	5.00	5.00	5.15
(2) Total runoff, inches	0.81	0.43	0.53	0.96
(3) Total retention (rainfall minus runoff), inches	4.30	4.57	4.47	4.19
(4) Maximum rate of runoff, cubic feet per second	2.92	18.1	42.6	176
(5) Maximum rate of runoff, c f s per acre	0.89	0.79	0.81	1.03

The information from a cover- and tillage-map made on July 29, 1940, is summarized in Table 3, to show the type and condition of vegetal cover at the time of the storm.

Table 3--Vegetal cover in per cent of area, July 29, 1940

Vegetal cover	Watershed and area in acres			
	W-I 330	W-II, 22.8	W-III, 52.5	W-IV, 171
Corn, 6 to 8 feet high	19	22	13	25
Small grains, very little cut	24	26	20	32
Hay, second crop, 10 to 12 inches high	31	52	32	22
Pasture	22	0	32	17
Roads and buildings	4	0	3	4

The partial data for this storm show that even intense rainfall (with the highest intensities occurring towards the end of the rain) produced low rates and very small amounts of runoff. This was further confirmed by records from another intense rain which occurred several days later. On August 3, 1940, 2.30 inches of rain fell between 6:13 p.m. and 7:05 p.m. The maximum intensities for various durations and their estimated frequencies are as follows:

Rainfall-intensity, inches per hour	Duration, minutes	Estimated frequency, years
4.8	5	2
4.5	10	Nearly 5
4.4	15	Nearly 10
3.8	30	25

A partial record of this rain and the resulting runoff is given in Table 4.

Table 4--Rainfall- and runoff-data for storm of August 3, 1940

Item	Watershed and area in acres			
	W-I, 330	W-II, 22.8	W-III, 52.5	W-IV, 171
(1) Total rainfall, 6:13 to 7:05 p.m., inches	2.27	2.38	2.27	2.31
(2) Total runoff, inches	0.41	0.32	0.25	0.48
(3) Total retention (rainfall minus runoff), inches	1.86	2.06	2.02	1.83
(4) Maximum rate of runoff, c f s	258	23.7	36.6	164
(5) Maximum rate of runoff, c f s per acre	0.78	1.04	0.70	0.96

The total rainfall, the intensities, and the storm-pattern, as well as antecedent rainfall, of the rain of August 3 were different from those of July 25 and 26, while the cover- and tillage-conditions remained unchanged. The high intensities occurred at the beginning of the rain, and this accounts for the lower maximum rates of runoff on all but W-II. Probably the higher rate of W-II is due to the higher rainfall-intensity for the 15-minute duration, which did not affect the larger watersheds.

The summaries for the two storms, and the brief description of the permanent watershed-characteristics and of the conditions of vegetal cover which could be included in this short paper are far from complete. No further attempt will be made to discuss the differences in runoff from the several watersheds. Such a discussion involving the consideration of numerous items of information is beyond the scope of this article. The partial data are, however, sufficient to show rather conclusively that runoff (both as to rates and amounts) from the Fennimore watersheds is decidedly low. The deep permeable soil with the existing vegetal cover is capable of absorbing large quantities of rainfall even when the intensities are high. The low drainage-density together with broad waterways covered with a heavy growth of vegetation reduce the peak-rates of runoff.

U. S. Soil Conservation Service,
Fennimore, Wisconsin

ESTIMATING ANNUAL YIELD FROM UNGAGED DRAINAGE-BASINS AND EFFECT OF LAND-USE TREATMENT ON SURFACE-RUNOFF

C. S. Jarvis and H. C. Murto
(Presented by C. S. Jarvis)

A promising concept for flood-forecasting is to make use of index-areas as nearly as may be representative of the drainage-basins under consideration, relying on the records of their behavior in the past to show the probable relationship between index-area and main drainage-basin during and following storms. Obviously, a variation in the storm-pattern, such as would make the index area non-representative of the drainage-basin, by reason of too much or too little rainfall received thereon, would result in misguidance instead of reliable forecasts, and therefore suggests the advisability of using more than one index-area. For example, the drainage-area of Ralston Creek, Iowa, has been shown to serve in some instances as a satisfactory index for Iowa River, and in other instances to be less reliable [see 1 of "References" at end of paper]; likewise for Home Creek, Ohio, of the Muskingum River system [2].

The question has been raised repeatedly as to the value of runoff-data from experimental plots, fields, and small drainage-areas as indicative of probable runoff from larger drainage-basins. While it has been conceded that other factors may enter into the relationship between the small plots or elementary areas and the entire watershed under consideration, it still is claimed that the relative behavior of small plots under different treatments and land-use should provide a fairly dependable measure of the surface-runoff to be expected under similar conditions.

Thus, it was found at Tyler, Texas, that various percentages of the rainfall appeared as surface-runoff from row-crop land, ranging as high as 30 per cent in many cases, and occasionally higher than 60 per cent, while the yield from land in Bermuda grass, on similar soil and slope, seldom attained one per cent runoff, even under storms of moderate intensity with rainfall-depth ranging up to approximately four inches per day.

The question naturally arises as to the probability of flood-flows from row-crop areas being some 30 times the yield from equal acreage in Bermuda grass, and whether a watershed divided equally for those two crops would yield a mean of their percentages, or some 15 per cent of the rainfall as surface-runoff.

It has been shown by Merrill Bernard [3] that the answer to this problem depends partly on the location of the respective land-use areas. Thus, the grass-covered land among the headwaters, together with row-crop land in the valley, would produce less runoff-volumes and peaks than would the same in reverse locations. Row-crop lands on the headwaters, with their facilities for rapid concentration of runoff, would seem to superimpose in part upon the more sluggish assembly of runoff-grassland in the lower valley. Thus, flood assembly and routing seem to be governed by the same fundamental principles as those underlying traffic control, where the ideal sought is a regulated, nearly-continuous flow within normal capacity, and avoidance of congestion.

Flood-routing compared with traffic control--For the prevention of highway overcrowding, and to speed traffic, there are (1) the detours provided in modern planning to avoid the already congested districts, (2) the diversions of heavily-laden vehicles from designated boulevards, primarily designed for lighter units and higher speeds, and (3) the control of loadings as would drop objectionable material on the road surface, tending to endanger and impede the traffic for which the highways were designed. All these practices seem to have something of their counterparts in channels designed for accommodating floods, even to the desired control of heavy material that would reduce the channel cross-section and impair the flow-capacity below requirement.

Portions of the rainfall that are diverted into ground-water storage or flow may contribute somewhat to a later rise, as well as to low-water flow. Such accretions are insignificant when compared with major flood-peaks, even though they may be the larger part of low-season flow.

Limitations in use of index-area data--While the surface-runoff from plots or fields may indicate the probable behavior of such portions of a large drainage-area as they represent, there is always the question as to what these respective portions may be; also, there is the rainfall-distribution, as uncertain as the weather, and capable of upsetting all calculations and predictions when it happens to be irregular or restricted to narrow belts.

Furthermore, on coarse gravelly soils, or on slopes of detrital cones, or on areas underlain by cavernous limestone, in only rare instances have the flood-contributions gone practically unimpeded into well-defined stream-channels, with little evidence of surface-runoff. Under such conditions, the lack of runoff from the surface of such areas is obviously accounted for by flow through systems of underground channels.

For ordinary soils and valley-fills, the velocity of ground-water is so slow as to insure some seepage at favorable outcrops for hours, days, or even weeks after copious rains. In this manner, areas regularly supplied with irrigation-water have produced perennial springs, or have required the drainage of adjacent lands down the slope; and, to a lesser degree, such results have followed the operation of conservation programs, producing perennial flow in place of the former intermittent yield.

Application to the North Concho River, Texas--During the record-breaking flood of September, 1936, on the North Concho River in central Texas, some 10,000 acres of gently sloping valley-land, representing approximately one per cent of the entire drainage area above San Angelo, Texas, had level or closed terraces that retained the entire rainfall of some 15 inches from the three days of storm. This was due to the high infiltration-rate, from day to day, and the large storage-capacity back of each terrace embankment. If as much as 40 per cent of the North Concho Drainage-Area had been provided with contour-terraces that behaved as well, it seems obvious that 40 per cent of the surface-runoff would have been conserved. Certainly the flood-volume, and presumably the peak, would have been reduced correspondingly, provided the area suitable for terracing was fairly representative of the entire basin.

In this instance, some of the steeper country among the headwaters of Walnut and Grape creeks was capable of producing a much greater percentage of runoff than was possible from the valley-floor, for a given rainfall, and less amenable to surface-treatment for conservation-purposes. Some of the restricted areas on the plateau, intervening between those tributaries, disposed of their surface-runoff into natural depressions or sumps, locally known as "playas", marking the sites of solution-chambers or limestone caverns over which the roofs had collapsed.

One direct result of such accretions to ground-water as attended the storm was a pronounced and widely observed increase in the flow of springs and seeps among the headwaters, with one or more pumping wells being temporarily transformed into artesian wells for some weeks thereafter.

Many hydrologists, conscientiously seeking factual relations, have failed to connect such phenomena with measures for conservation and their value. There are always alternate lines of explanation or reasoning that may be supported by theories, and sometimes by physical observations, to account otherwise for fluctuations in ground-water levels and stream-discharge. It is difficult, however, to explain the rise in water-tables and the attendant augmentation of springs and wells without regarding underground storage as an automatic regulating reservoir, subtracting from the high runoff and later releasing the volume thus conserved at a gradually decreasing rate.

Recently established projects for the collection of hydrologic data naturally have included observations on small plots and lysimeters, as well as on subdivisions of drainage-basins, in the hope of connecting the index-relationship of small elementary areas with those of intermediate and larger sized drainage-areas. Great volumes of information are now available, and these are expanding with each year, showing the behavior of such index-areas under various land-use and cultural treatments, and the influence of various physical factors on surface-runoff, total yield, and peak-discharge. Examples of such data are included in Tables 1 and 2, also in the accompanying Figures 1 and 2, that utilize some of the tabulated observations as well as some new items.

If these results could readily be translated into corresponding discharge-hydrographs for the drainage-basins of intermediate and larger areas in the vicinity, then the forecasting and evaluation of flood-flows would be several stages ahead of what now can be done for practical purposes. Definite progress has been made by several independent investigators, in an attempt thus to apply the relative-yield factors and trend-curves, extending results from small areas progressively to larger and larger basins.

No one can gainsay reasonably that the surface-runoff data based on plots are fair indexes of what should be expected from larger areas of generally similar character, and under nearly comparable rainfall depths, as well as patterns of distribution. One of the many problems is to exclude the non-representative areas and to assign suitable values to their probable yield and rates of flow for the entire storm-periods under consideration.

Experience has demonstrated that much of the small-plot runoff-data is fairly consistent with surface-runoff observed for the surrounding basins, although ground-water accretions often represent much larger proportions of total yield during stormy periods than have been generally

Table 1--Summary of runoff-percentages from plots with various vegetal covers

Experiment-station	Plot No.	Cover	Years of record	Av. annual runoff		Plot-area, acres	Slope and remarks
				Depth, inches	Per cent		
lackland, Temple, Texas, progress-report, 1931-36	3	Continuous corn	6	4.660	14.22	0.01	4.0 per cent
	4	Rotation: Corn, oats, cotton	6	2.469	7.54	0.01	4.0 per cent
	6	Bermuda-grass	6	0.013	0.039	0.01	4.0 per cent
	12	Rotation: Cane, grass, oats, etc.	5	0.331	0.95	0.0463	3.5 per cent
Tables 16 and 17	13	Contour-row cotton	5	2.367	6.81	0.0847	3.5 per cent
	14	Rows down slope, cotton	5	5.435	15.63	0.0309	3.5 per cent
	18	Bermuda-grass	4	0.332	0.95	0.0286	3.5 per cent
	24	Rows down slope, cotton	4	8.884	24.07	0.1370	4 to 6 per cent
Table 23	Lysim.1	Fallow	1	7.780	19.52	3 ft diam	Level land
	Lysim.2	Bermuda-grass	1	0.171	0.43	3 ft diam	Level land
	Lysim.8	Fallow	1	13.91	34.91	3 ft diam	4 per cent
ur, Texas, Bull. 587, July, 1940	Tab.8	Cotton	14	3.09	15.4		2 per cent
		Fallow	14	4.09	20.3		2 per cent
		Buffalo-grass	14	1.04	5.2		About 4.85 inches first year, from new grass
	Tab.9	Cotton	13	1.41	7.53		Rows on slope
		Cotton	13	0.88	4.70		Rows on contour
		Cotton	13	0.0	0.0		Closed level-terraces
		Cotton	3	3.80	18.72		2 per cent, 1934-36
report covering 1934-36		Fallow	3	7.73	38.10		2 per cent, 1934-36
		Grass	3	1.52	7.50		2 per cent, 1934-36
ler, Texas, progress-report, 1931-36	1	Woods	6	1.13	2.69		Burned in March; 12.5 per cent
	2	Woods	6	0.227	0.54		Virgin woods; 12.5 per cent
	4	Cotton	6	7.48	18.32	0.01	Continuous; 8.75 per cent
	8	Clipped Bermuda-grass	6	0.47	1.15	0.01	Continuous; 8.75 per cent
	10	Desurfaced cotton	6	10.75	26.33	0.01	Continuous; 8.75 per cent

realized. It even appears as if the addition of moisture to the upper horizons of a soil-column approaching saturation may instantly release a corresponding amount at the base of the column, so delicately are the gravitational, capillary, and surface-tension forces balanced.

Probably the correlation between total yields of runoff for plots and for larger drainage-basins, either in whole or in part, has progressed much further than has the development of synthetic hydrographs for large streams, based on plot-runoff data. However, recent progress in the application of unit-hydrographs, distribution-graphs, and flood-routing procedure has covered effectively much of the intermediate territory, and holds promise of a fairly satisfactory correlation of data from small to large areas.

Transition to larger areas--A broad concept of the problem would recognize the essential similarities among all index-area derivations of discharge, irrespective of their relative size. Whether a forecast is made of the runoff from an acre, or from 10,000 acres, or from as many square miles, based on the observed behavior of one or more small plots, lysimeters, or other index-areas representing any minor fraction, or even a major fraction of the larger watershed, nearly the same fundamental considerations are involved, differing mainly in degree, or weight, or numerical values, expressed as coefficients.

Furthermore, the unit-hydrograph and associated procedures have shown how closely related are flood-peaks and flood-volumes generally, each stream and station-record seemingly a law unto itself, and reflecting the distinctive characteristics representing the summation of physical

Table 2--Summary of runoff-percentages from plots with various vegetal covers

Experiment-station	Date	Cover	Rainfall, inches	Storm-runoff		Slope
				Depth, inches	Per cent	
Bethany, Missouri	Apr.3-4,1936	Fallow	3.28	1.71	52.2	8.0 per cent
		Grass	3.28	1.27	38.8	8.0 per cent
		Clover-stubble	3.28	0.96	29.3	8.0 per cent
Guthrie, Oklahoma	Aug. 20,1937	Fallow	3.28	1.31	40.0	7.7 per cent
		Grass	3.28	0	0	7.7 per cent
		Woods	3.28	0	0	5.2 per cent
Zanesville, Ohio	June 20-21,1937	Fallow	3.37	2.66	78.8	12 per cent
		Grass	3.37	1.03	30.6	12 per cent
		Woods	3.37	0.50	14.9	12 per cent
Clarinda, Iowa	May 6, 1937	Fallow	1.43	1.10	76.9	9.0 per cent
		Grass	1.43	0	00	9.0 per cent
		Alfalfa	1.43	0	0	9.0 per cent
Tyler, Texas	Dec. 6, 1936	Sod, dormant	2.66	0.02	0.7	8.75 per cent
		Cotton, dead	2.66	1.78	66.9	8.75 per cent
Tyler, Texas	Nov.15, 1937	Cotton, 26-inch	1.61	1.02	63.3	8.75 per cent
		Bermuda-grass	1.61	0.04	2.5	8.75 per cent
		Bare ground	1.61	1.11	69.0	8.75 per cent

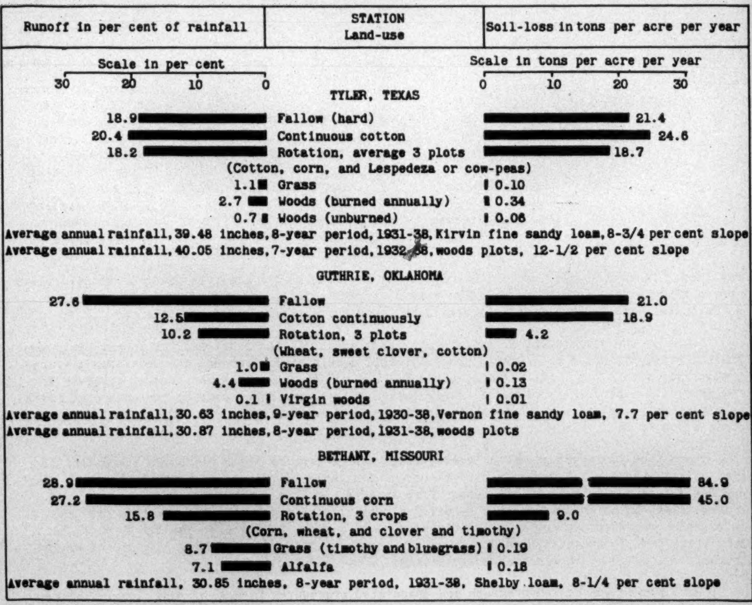


Fig. 1--Effects of land-use on average annual runoff and soil-loss

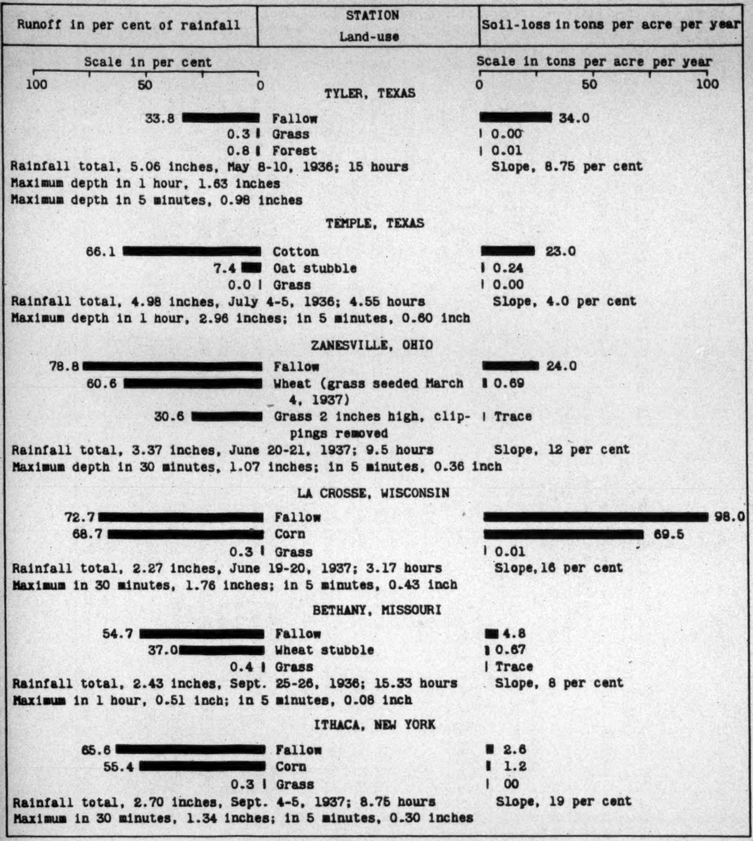


Fig. 2--Effects of land-use on runoff and soil-loss during storms that produced greatest runoff-depths

influences within the respective drainage-areas. Naturally, these same characteristics are traceable to some degree in the amount and variation of yield, year by year, or month by month, or day by day. This concept has guided some recent research in hydrologic data as related to land-use, from which interesting relationships have been disclosed, as outlined below.

A natural extension from experimental plots or small index-areas is the use of fairly important tributaries chosen to represent various portions of large drainage-basins, such as are included in the Mississippi River System. During the search for such widely distributed gaged areas as bases for independently estimating the discharge of main tributaries, and finally of the Mississippi River at Vicksburg, Mississippi, it was found that official discharge-records of the Tennessee River at Chattanooga, Tennessee, and of the Mississippi River at LeClaire, Iowa, extended back to include the water-year 1874-1875.

Testing the discharge from these two areas, aggregating 9.4 per cent of the total drainage above Vicksburg, against the unofficial quantities tentatively selected from the Vicksburg hydrograph and the rating tables of the Mississippi River Commission, for the ten-year period 1875 to 1884, inclusive, it was found that the departures from the mean discharge-relationship ranged from +30.2 per cent to -19.9 per cent for the water-year, with mean departure of ±12.1 per cent,

Table 3--Tests of "sampling method" for determining stream-discharge through its observed relationship to measured yield during concurrent years of record

(Derivation of Mississippi-River discharge from long-period records of tributaries representing 9.6 per cent of the drainage-area above Vicksburg, Mississippi)

Years of record, ending	Drainage-basin, station, and area in square miles								Total drainage-area 1,144,500 square miles			
	Mississippi River Le Claire, Iowa 88,500		Tennessee River Chattanooga, Tenn. 21,390		Total gaged area 109,990		Total ungaged area 1,034,510		Water-year		Calendar year	
	Water-year (Oct - Sep)	Cal.-year (Jan-Dec)	Water-year (Oct - Sep)	Cal.-year (Jan-Dec)	Water-year	Calendar-year	Water-year	Calendar-year	1000 c f s	csm	1000 c f s	csm
1875	57,900	55,200	54,700	57,620	112,600	112,820	475,600	516,180	588.2	0.514	629	0.550
1876	67,400	68,500	47,200	41,260	114,600	109,760	622,900	610,240	737.5	0.644	720	0.629
1877	44,900	45,000	31,800	35,740	76,700	80,740	483,800	487,260	550.5	0.481	568	0.496
1878	43,800	43,500	30,000	30,940	73,800	74,440	498,900	481,560	572.7	0.500	556	0.486
1879	40,800	40,700	33,400	34,190	74,200	74,890	387,000	372,110	461.2	0.403	447	0.391
5-year Totals	254,800	252,900	197,100	199,750	451,900	452,650	2,458,200	2,467,350	2,910.1	2.543	2,920	2.552
Means	50,960	50,580	39,420	39,950	90,380	90,530	491,640	493,470	582.0	0.509	584	0.510
1880	63,700	62,500	42,600	41,550	106,300	104,050	399,900	407,950	506.2	0.442	512	0.447
1881	58,200	85,800	35,700	37,330	93,900	123,130	453,800	467,870	547.7	0.479	591	0.516
1882	94,500	71,400	58,500	53,730	153,000	125,130	622,000	604,870	775.0	0.677	730	0.638
1883	65,600	61,800	38,800	39,650	104,400	101,450	519,800	543,550	624.2	0.545	645	0.564
1884	56,600	66,400	51,500	49,510	108,100	115,910	588,700	560,090	696.8	0.609	676	0.591
5-year Totals	338,600	347,900	227,100	221,770	565,700	569,670	2,584,200	2,584,330	3,149.9	2.752	3,154	2.756
Means	67,720	69,580	45,420	44,354	113,140	113,934	516,840	516,866	630.0	0.550	630.8	0.551
10-year Totals	593,400	600,800	424,200	421,520	1,017,600	1,022,320	5,042,400	5,051,680	6,060.0		6,074	
Means	59,340	60,080	42,420	42,152	101,760	102,234	504,240	505,168	606.0	0.529	607.4	0.531

as shown in Table 3. The addition of the Missouri River at Fort Benton, Montana, the Kanawha River at Kanawha Falls, West Virginia, and the Cumberland River at Nashville, Tennessee, and the substitution of Keokuk, Iowa, for LeClaire, Iowa, afforded enlarged index-areas aggregating 16.3 per cent of the total drainage above Vicksburg.

Table 3--Tests of "sampling method" for determining stream-discharge through its observed relationship to measured yield during concurrent years of record--Concluded

(Derivation of Mississippi-River discharge from long-period records of tributaries representing 9.6 per cent of the drainage-area above Vicksburg, Mississippi)

Years of record, ending	Yields in csm				Ratio				Departures			
	Gaged = Y_g		Ungaged = Y_u		(Y_u/Y_g)		(Y_{u+g}/Y_g)		Water-year, csm	Cal.-year, csm	Per cent record mean	
	Water-year	Cal.-year	Water-year	Cal.-year	Water-year	Cal.-year	Water-year	Cal.-year			Water-year	Cal.-year
1875	1.024	1.026	0.459	0.499	0.448	0.486	0.502	0.536	-0.070	-0.036	-12.2	- 6.3
1876	1.042	0.998	0.602	0.590	0.578	0.591	0.618	0.630	+0.046	+0.058	+ 8.0	+10.1
1877	0.697	0.734	0.466	0.471	0.671	0.642	0.690	0.676	+0.118	+0.104	+20.6	+18.2
1878	0.671	0.677	0.482	0.465	0.718	0.687	0.745	0.718	+0.173	+0.146	+30.2	+25.5
1879	0.675	0.681	0.374	0.360	0.554	0.529	0.597	0.574	+0.025	+0.002	+ 4.4	+ 0.3
5-year Totals	4.109	4.116	2.385	2.385	2.969	2.935	3.152	3.134	+0.362 -0.070	+0.310 -0.036	+63.4 -12.2	+54.1 - 6.3
Means	0.822	0.823	0.475	0.477	0.578	0.580	0.619	0.620	+0.047	+0.048	+ 8.2	+ 8.4
1880	0.966	0.946	0.387	0.394	0.401	0.416	0.458	0.473	-0.114	-0.099	-19.9	-17.3
1881	0.854	1.119	0.439	0.452	0.514	0.404	0.561	0.461	-0.011	-0.111	- 1.9	-19.4
1882	1.391	1.138	0.601	0.585	0.432	0.513	0.487	0.561	-0.085	-0.011	-14.9	- 1.9
1883	0.949	0.922	0.502	0.525	0.529	0.569	0.574	0.612	+0.002	+0.040	+ 0.3	+ 7.0
1884	0.983	1.054	0.569	0.541	0.579	0.513	0.620	0.561	+0.048	-0.011	+ 8.4	- 1.9
5-year Totals	5.143	5.179	2.498	2.497	2.455	2.416	2.700	2.668	+0.050 -0.210	+0.040 -0.232	+ 8.7 -36.7	+ 7.0 -41.5
Means	1.029	1.036	0.500	0.500	0.486	0.483	0.535	0.532	-0.037	-0.040	- 6.5	- 7.0
10-year Means	0.925	0.929	0.487	0.488	0.526	0.525	0.572	0.572	±0.069	±0.062	±12.1	±10.9

Table 4--Section A: Tests of "sampling method" for determining stream-discharge through its observed relationship to measured yield during concurrent years of record (Derivation Mississippi-River discharge from long-period records, tributaries representing 16.3 per cent drainage-area above Vicksburg, Mississippi)

Years of record, ending	Drainage-basin, station, and area in square miles										Total gaged area, 186,217 sq. miles		Total ungaged area, 958,283 sq. miles	
	Missouri River, Fort Benton, Mon., 24,000		Mississippi River, Keokuk, Iowa, 119,000		Kanawha River, Kanawha Falls, W. Va., 8,367		Cumberland River, Nashville, Tenn., 12,860		Tennessee River, Chattanooga, Tenn., 21,390					
(1)	Water-year,[a] cfs (2)	Cal.-year,[b] cfs (3)	Water-year, cfs (4)	Cal.-year, cfs (5)	Water-year, cfs (6)	Cal.-year, cfs (7)	Water-year, cfs (8)	Cal.-year, cfs (9)	Water-year, cfs (10)	Cal.-year, cfs (11)	Water-year, cfs (12)	Cal.-year, cfs (13)	Water-year, cfs (14)	Cal.-year, cfs (15)
1875	(8,200)	(8,400)	(73,000)	(69,500)	(22,000)	(23,000)	(27,100)	(28,400)	54,700	57,620	185,000	186,920	403,200	442,080
1876	(12,600)	(12,100)	(84,000)	(85,500)	(19,000)	(16,500)	(24,000)	(21,000)	47,200	41,260	186,800	176,360	550,700	543,640
1877	(7,400)	(7,000)	(56,000)	(56,200)	(12,000)	(13,000)	(16,000)	(18,000)	31,800	35,740	123,200	129,940	427,300	438,060
1878	(7,800)	(8,500)	(55,000)	60,900	17,200	18,100	(15,000)	(15,500)	30,000	30,940	125,000	133,940	447,700	422,060
1879	(8,800)	(9,200)	49,500	48,000	13,400	11,400	(17,000)	(17,400)	33,400	34,190	122,100	120,190	339,100	326,810
5-year Totals	44,800	45,200	317,500	320,100	83,600	82,000	99,100	100,300	197,100	199,750	742,100	747,350	2,168,000	2,172,650
Means	8,960	9,040	63,500	64,020	16,720	16,400	18,200	20,060	39,420	39,950	148,420	149,470	433,600	434,530
1880	(9,100)	(10,100)	75,300	75,100	11,300	10,600	(21,000)	(20,500)	42,600	41,550	159,300	157,850	346,900	354,150
1881	(8,400)	(8,600)	79,700	115,000	10,500	11,600	(18,000)	(18,800)	35,700	37,330	152,300	191,330	395,400	399,670
1882	9,550	9,680	127,000	95,600	17,200	15,900	(29,000)	(26,600)	58,500	53,730	241,250	201,510	533,750	528,490
1883	9,320	9,220	82,600	79,700	12,200	13,100	(19,000)	(19,400)	38,800	39,650	161,920	161,070	462,280	483,930
1884	9,010	8,980	69,700	81,600	16,500	15,400	(25,000)	(24,000)	51,500	49,510	171,710	179,490	525,090	496,510
5-year Totals	45,380	46,580	434,300	447,000	67,700	66,600	112,000	109,300	227,100	221,770	886,480	891,250	2,263,420	2,262,750
Means	9,076	9,316	86,860	89,400	13,540	13,320	22,400	21,860	45,420	44,354	177,296	178,250	452,684	452,550
1885	9,620	9,620	89,700	78,700	9,430	11,300	(15,000)	(19,500)	28,300	37,200	152,050	156,320	437,150	453,780
1886	7,310	7,180	69,000	66,200	18,200	17,500	(26,500)	(24,100)	56,400	51,660	177,410	166,640	408,390	388,360
1887	10,400	10,700	53,800	51,600	13,400	12,000	(18,000)	(16,100)	40,200	36,430	135,800	126,830	364,000	352,170
1888	9,220	9,070	83,400	84,000	10,600	14,200	14,700	19,040	35,200	42,770	153,120	169,080	367,180	402,920
1889	5,410	5,000	42,500	40,700	18,100	17,300	19,700	19,580	42,100	38,330	127,810	120,910	331,890	342,090
5-year Totals	41,960	41,570	338,400	321,200	69,730	72,300	93,900	98,320	202,200	206,390	746,190	739,780	1,908,610	1,939,220
Means	8,392	8,314	67,680	64,240	13,946	14,460	18,780	19,664	40,440	41,278	149,238	147,956	381,722	387,844
1890	6,680	6,850	50,500	54,000	16,600	15,600	32,300	31,130	44,400	44,300	150,480	151,880	596,320	614,120
1891	9,980	10,300	50,200	46,300	19,700	19,200	26,000	24,360	51,200	49,130	157,080	149,290	500,620	446,710
1892	11,100	11,200	78,300	79,200	14,200	13,300	19,600	19,790	41,500	41,260	164,700	164,750	540,900	538,250
1893	10,100	10,100	63,700	62,900	13,100	15,000	17,200	16,370	37,800	37,320	141,900	141,690	460,300	450,310
1894	12,700	12,800	48,800	48,300	10,700	8,690	13,900	13,570	27,200	26,180	113,300	109,540	253,600	309,460
5-year Totals	50,560	51,250	291,500	290,700	74,300	71,790	109,000	105,220	202,100	198,190	727,460	717,150	2,351,740	2,358,850
Means	10,112	10,250	58,300	58,140	14,860	14,358	21,800	21,044	40,420	39,638	145,492	143,430	470,348	471,770

Table 4, Continued--Section A, Concluded

Years of record, ending	Total drainage-area 1,144,500 sq. miles				Yields in csm				Ratios				Departures			
	Water-year		Cal.-year		Gaged, Y_g		Ungaged, Y_u		(Y_u/Y_g)		(Y_{u+g}/Y_g)		In csm		Pct record mean	
	1000 cfs	csm	1000 cfs	csm	Water-year	Cal.-year	Water-year	Cal.-year	Water-year	Cal.-year	Water-year	Cal.-year	Water-year	Cal.-year	Water-year	Cal.-year
(1)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)
1875	588.2	.514	629	.550	0.993	1.004	.421	.461	.424	.459	.518	.548	-.143	-.113	-21.6	-17.1
1876	737.5	.644	720	.629	1.003	0.947	.575	.567	.573	.599	.642	.664	-.019	+.003	- 2.9	+ 0.5
1877	550.5	.481	568	.496	0.662	0.698	.446	.457	.674	.655	.727	.711	+.066	+.040	+10.0	+ 6.0
1878	572.7	.500	556	.486	0.671	0.719	.467	.440	.696	.612	.745	.676	+.084	+.015	+12.7	+ 2.3
1879	461.2	.403	447	.391	0.656	0.645	.354	.341	.540	.529	.614	.606	-.047	-.055	- 7.1	- 8.3
5-year																
Totals	2,910.1	....	2,920	....	.....	.....	....	....	....	....	....	....	.....	.....	.....	.....
Means	582.0	.509	584.0	.510	0.797	0.803	.452	.453	.567	.564	.639	.635	-.022	-.026	- 3.3	- 3.9
1880	506.2	.442	512	.447	0.855	0.848	.362	.370	.423	.436	.517	.527	-.144	-.134	-21.8	-20.3
1881	547.7	.479	591	.516	0.818	1.027	.413	.417	.505	.406	.586	.502	-.075	-.159	-11.3	-24.0
1882	775.0	.677	730	.638	1.296	1.082	.557	.551	.430	.509	.522	.590	-.139	-.071	-21.0	-10.7
1883	624.2	.545	645	.564	0.870	0.865	.482	.505	.554	.584	.626	.652	-.035	-.009	- 5.3	- 1.4
1884	696.8	.609	676	.591	0.922	0.964	.548	.518	.594	.537	.661	.613	.000	-.048	0.0	- 7.3
5-year																
Totals	3,149.9	....	3,154	....	.....	.....	....	....	....	....	....	....	.....	.....	.....	.....
Means	630.0	.550	630.8	.551	0.952	0.957	.472	.472	.496	.493	.578	.576	-.083	-.085	-12.5	-12.9
1885	589.2	.515	610	.533	0.817	0.839	.456	.474	.558	.565	.630	.635	-.031	-.026	- 4.7	- 3.9
1886	585.8	.512	555	.485	0.953	0.895	.426	.405	.447	.453	.537	.542	-.124	-.119	-18.7	-18.0
1887	499.8	.436	479	.419	0.729	0.681	.380	.367	.521	.539	.598	.615	-.063	-.046	- 9.5	- 7.0
1888	520.3	.454	572	.500	0.822	0.908	.383	.420	.466	.463	.552	.551	-.109	-.110	-16.5	-16.6
1889	459.7	.402	463	.405	0.686	0.649	.346	.357	.504	.550	.586	.624	-.075	-.037	-11.3	- 5.6
5-year																
Totals	2,654.8	....	2,679	....	.....	.....	....	....	....	....	....	....	.....	.....	.....	.....
Means	531.0	.464	535.8	.468	0.801	0.795	.398	.405	.497	.509	.579	.588	-.082	-.073	-12.4	-11.0
1890	746.8	.653	766	.669	0.808	0.816	.622	.641	.770	.786	.808	.820	+.147	+.159	+22.2	+24.0
1891	657.7	.575	596	.521	0.844	0.802	.522	.466	.618	.581	.681	.650	+.020	-.011	+ 3.0	- 1.7
1892	705.6	.616	703	.614	0.884	0.885	.564	.562	.638	.635	.697	.694	+.036	+.033	+ 5.4	+ 5.0
1893	602.2	.526	592	.517	0.762	0.761	.480	.470	.630	.618	.690	.679	+.029	+.018	+ 4.4	+ 2.7
1894	366.9	.321	419	.366	0.608	0.588	.265	.323	.436	.549	.528	.622	-.133	-.039	-20.1	- 5.9
5-year																
Totals	3,079.2	....	3,076	....	.....	.....	....	....	....	....	....	....	.....	.....	.....	.....
Means	615.8	.538	615.2	.538	0.781	0.770	.491	.492	.629	.639	.689	.699	+.028	+.038	+ 4.2	+ 5.7

Notes: Parentheses () enclose derived, unofficial, or partly estimated basic data among official data; only the discharges of 1932-39 at Vicksburg are from United States Geological Survey. [a]Water-year is the 12 months from October to September. [b]Calendar-year (abbreviated as Cal.-year) is the 12 months January to December.

Table 4, continued--Section B [For designation of columns as numbered in parentheses see pages -]

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
1895	8,490	8,030	31,200	30,400	11,800	11,600	15,200	15,370	33,300	32,350	99,990	97,750	187,610	191,250
1896	9,570	9,870	44,400	47,300	11,600	13,900	16,500	18,000	28,700	31,240	110,770	120,310	317,830	335,690
1897	9,210	8,940	71,200	68,000	16,300	14,300	24,400	22,990	44,100	42,090	165,210	156,320	492,790	475,680
1898	10,600	10,600	42,500	42,500	12,200	14,900	15,800	17,610	29,800	34,970	110,900	120,580	469,100	501,420
1899	11,900	12,300	55,600	58,100	18,100	15,100	27,500	25,770	48,800	43,840	161,900	155,110	464,500	433,890
5-year Totals	49,770	49,740	244,900	246,300	70,000	69,800	99,400	99,740	184,700	184,490	648,770	650,070	1,931,830	1,937,930
Means	9,954	9,948	48,980	49,260	14,000	13,960	19,880	19,948	36,940	36,898	129,754	130,014	386,366	387,586
1900	9,090	8,630	47,500	57,400	10,200	12,600	13,900	16,510	29,900	32,420	110,590	127,560	293,110	323,440
1901	7,820	7,670	60,700	48,500	21,100	21,600	21,200	20,010	48,200	50,720	159,020	148,500	292,880	261,500
1902	7,340	7,310	45,100	61,900	15,000	13,100	19,700	22,070	42,400	39,110	129,540	143,490	324,560	364,510
1903	8,040	8,510	86,800	93,900	13,900	12,500	26,300	22,890	43,500	40,900	178,540	178,700	582,960	554,300
1904	8,880	8,430	73,700	65,500	7,590	7,510	12,500	11,800	21,900	21,950	124,570	115,190	424,230	409,810
5-year Totals	41,170	40,550	313,800	327,200	67,790	67,310	93,600	93,280	185,900	185,100	702,260	713,440	1,917,740	1,913,560
Means	8,234	8,110	62,760	65,440	13,558	13,462	18,720	18,656	37,180	37,020	140,452	142,668	383,548	382,712
1905	5,660	5,570	80,500	82,600	10,300	11,300	12,800	16,060	30,900	33,710	140,160	149,240	351,840	397,760
1906	6,930	6,730	87,600	87,100	12,800	16,000	17,600	19,460	37,800	45,170	162,730	174,460	407,570	424,540
1907	12,300	13,100	80,600	78,900	18,300	17,000	23,600	20,250	43,400	37,830	178,200	167,080	622,800	572,920
1908	13,800	14,300	77,000	71,500	16,600	15,200	17,800	16,150	40,300	39,250	165,500	156,400	563,000	560,600
1909	13,000	12,100	67,700	73,400	12,900	12,200	21,100	20,950	49,700	47,150	164,400	165,800	474,500	479,200
5-year Totals	51,690	51,800	393,400	393,500	70,900	71,700	92,900	92,870	202,100	203,110	810,990	812,980	2,419,710	2,435,020
Means	10,338	10,360	78,680	78,700	14,180	14,340	18,580	18,574	40,420	40,622	162,198	162,596	483,942	487,004
1910	7,780	7,720	49,600	41,600	10,300	10,300	17,500	18,240	29,500	29,190	114,680	107,050	367,020	366,950
1911	7,790	7,840	35,500	50,500	10,600	12,200	18,700	21,450	31,200	34,480	103,790	126,470	307,910	333,530
1912	9,150	9,780	72,300	62,200	13,500	12,100	29,600	26,520	42,800	40,130	167,350	150,730	538,350	507,270
1913	11,200	10,900	54,100	53,300	11,500	12,800	22,800	21,990	36,000	34,820	135,600	133,810	477,900	484,190
1914	8,690	8,490	49,500	50,100	11,200	10,600	11,800	15,310	22,400	27,310	103,590	111,810	283,910	265,190
5-year Totals	44,610	44,730	261,000	257,700	57,100	58,000	100,400	103,510	161,900	165,930	625,010	629,870	1,975,090	1,957,130
Means	8,922	8,946	52,200	51,540	11,420	11,600	20,080	20,702	32,380	33,186	125,002	125,974	395,018	391,426
1915	8,810	8,880	69,600	75,500	11,100	12,000	19,800	25,750	34,600	37,010	143,910	159,140	603,290	516,860
1916	10,800	10,500	88,400	82,300	14,900	(12,900)	28,400	20,220	44,700	38,770	187,200	164,690	614,000	558,310
1917	13,300	13,700	62,000	59,200	12,200	(11,900)	27,400	27,100	44,400	43,280	159,300	155,180	410,100	413,820
1918	8,000	7,670	51,300	52,300	11,900	(13,000)	18,000	20,140	28,800	35,830	118,000	128,940	271,500	284,060
1919	5,070	4,420	65,800	71,000	15,100	14,300	19,400	25,650	40,300	37,200	145,670	152,570	402,030	496,430
5-year Totals	45,980	45,170	337,100	340,300	65,200	64,100	113,000	118,860	192,800	192,090	754,080	760,520	2,300,920	2,269,480
Means	9,196	9,034	67,420	68,060	13,040	12,820	22,600	23,772	38,560	38,418	150,816	152,104	460,184	453,896

(1)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)
1895	287.6	.251	289	.253	0.537	0.525	.196	.200	.365	.381	.467	.482	-.194	-.179	-29.3	-27.1
1896	428.6	.374	456	.398	0.595	0.646	.332	.350	.558	.542	.629	.616	-.032	-.045	- 4.8	- 6.8
1897	658.0	.575	632	.552	0.887	0.839	.514	.496	.579	.591	.648	.658	-.013	-.003	- 2.0	- 0.5
1898	580.0	.507	622	.543	0.596	0.648	.490	.523	.822	.807	.851	.838	+.190	+.177	+28.7	+26.8
1899	626.4	.547	589	.515	0.869	0.833	.485	.453	.558	.544	.629	.618	-.032	-.043	- 4.8	- 6.5
5-year Totals	2,580.6	....	2,588	....	.....	.....	....	....	....	....	....	....	.....	.....	.....	.....
Means	516.1	.451	517.6	.452	0.697	0.699	.403	.404	.578	.578	.647	.647	-.014	-.014	- 2.1	- 2.1
1900	403.7	.353	451	.394	0.594	0.685	.306	.338	.515	.493	.594	.575	-.065	-.086	- 9.8	-13.0
1901	451.9	.395	410	.358	0.854	0.797	.306	.273	.358	.343	.463	.449	-.198	-.212	-29.9	-32.1
1902	454.1	.397	508	.444	0.696	0.771	.339	.380	.487	.493	.570	.576	-.091	-.085	-13.8	-12.9
1903	761.5	.665	733	.640	0.959	0.960	.608	.578	.634	.602	.693	.667	+.032	+.006	+ 4.8	+ 0.9
1904	548.8	.479	525	.459	0.669	0.619	.443	.428	.662	.691	.716	.742	+.055	+.081	+ 8.3	+12.2
5-year Totals	2,620.0	....	2,627	....	.....	.....	....	....	....	....	....	....	.....	.....	.....	.....
Means	524.0	.458	525.4	.459	0.754	0.766	.400	.399	.531	.521	.607	.599	-.054	-.062	- 8.2	- 9.4
1905	492.0	.430	547	.478	0.753	0.801	.367	.415	.487	.518	.571	.597	-.090	-.064	-13.6	- 9.7
1906	570.3	.498	599	.523	0.874	0.937	.425	.443	.486	.473	.570	.558	-.091	-.103	-13.8	-15.6
1907	801.0	.700	740	.647	0.957	0.897	.650	.598	.679	.667	.731	.721	+.070	+.060	+10.6	+ 9.1
1908	728.5	.637	717	.627	0.889	0.840	.588	.585	.661	.696	.717	.746	+.056	+.085	+ 8.5	+12.9
1909	638.9	.558	645	.564	0.883	0.890	.495	.500	.561	.562	.632	.634	-.029	-.027	- 4.4	- 4.1
5-year Totals	3,230.7	....	3,248	....	.....	.....	....	....	....	....	....	....	.....	.....	.....	.....
Means	646.1	.565	649.6	.568	0.871	0.873	.505	.508	.580	.582	.649	.651	-.012	-.010	- 1.8	- 1.5
1910	481.7	.421	474	.414	0.616	0.575	.383	.383	.622	.666	.683	.720	+.021	+.059	+ 3.2	+ 8.9
1911	411.7	.360	460	.402	0.557	0.679	.321	.348	.576	.513	.646	.592	-.015	-.069	- 2.3	-10.4
1912	705.7	.617	658	.575	0.899	0.809	.562	.529	.625	.654	.686	.711	+.025	+.050	+ 3.8	+ 7.6
1913	613.5	.536	618	.540	0.728	0.719	.499	.505	.685	.702	.736	.751	+.075	+.090	+11.3	+13.6
1914	387.5	.338	377	.329	0.556	0.600	.296	.277	.532	.462	.608	.548	-.053	-.113	- 8.0	-17.1
5-year Totals	2,600.1	....	2,587	....	.....	.....	....	....	....	....	....	....	.....	.....	.....	.....
Means	520.0	.454	517.4	.452	0.671	0.676	.412	.408	.614	.604	.677	.669	+.016	+.008	+ 2.4	+ 1.2
1915	747.2	.653	676	.591	0.773	0.855	.630	.539	.815	.630	.845	.691	+.184	+.030	+27.8	+ 4.5
1916	801.2	.700	723	.632	1.005	0.884	.641	.583	.638	.660	.697	.715	+.036	+.054	+ 5.4	+ 8.2
1917	569.4	.498	569	.497	0.855	0.833	.428	.432	.501	.519	.582	.597	-.079	-.064	-11.9	- 9.7
1918	389.5	.340	413	.361	0.634	0.692	.283	.296	.446	.428	.536	.522	-.125	-.139	-18.9	-21.0
1919	547.7	.478	649	.567	0.782	0.819	.420	.518	.537	.632	.611	.692	-.050	+.031	- 7.6	+ 4.7
5-year Totals	3,055.0	....	3,030	....	.....	.....	....	....	....	....	....	....	.....	.....	.....	.....
Means	611.0	.534	606.0	.529	0.810	0.817	.480	.474	.593	.580	.659	.647	-.002	-.014	- 0.3	- 2.1

Table 4, continued--Section C [For designation of columns as numbered in parentheses see pages -]

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
1920	7,520	8,070	71,500	66,100	13,100	12,500	35,400	27,860	49,300	50,180	176,820	164,710	630,680	540,290
1921	7,880	7,800	46,300	48,100	8,970	9,660	16,200	18,460	36,800	34,840	116,150	118,860	392,450	426,140
1922	8,310	8,280	59,700	56,400	13,200	11,700	26,900	25,390	43,800	42,940	151,910	144,710	463,890	477,290
1923	7,660	7,730	39,000	39,300	11,200	11,200	25,100	24,220	42,400	40,910	125,360	123,360	440,140	488,640
1924	6,460	6,320	51,300	52,700	13,400	14,100	20,000	20,090	34,300	35,540	125,460	128,750	490,640	458,250
5-year Totals	37,830	38,200	267,800	262,600	59,870	59,160	123,600	116,020	206,600	204,410	695,700	680,390	2,417,800	2,390,610
Means	7,566	7,640	53,560	52,520	11,974	11,832	24,720	23,204	41,320	40,882	139,140	136,078	483,560	478,122
1925	7,790	8,420	37,400	37,000	8,540	7,840	13,100	15,190	22,200	22,970	89,030	91,420	241,670	285,580
1926	7,300	6,860	45,400	56,000	8,990	12,100	17,400	22,890	26,200	31,370	105,290	129,220	358,010	404,780
1927	10,800	11,500	75,300	69,400	15,000	(13,200)	32,100	24,670	43,200	37,880	176,400	156,650	781,200	748,350
1928	9,910	9,500	63,700	71,400	13,300	(13,800)	24,800	25,870	42,700	43,910	154,410	164,480	557,790	531,520
1929	6,880	6,760	80,700	67,800	12,400	14,700	27,700	28,990	48,500	52,870	176,180	171,120	606,820	597,880
5-year Totals	42,680	43,040	302,500	301,600	58,230	61,640	115,100	117,610	182,800	189,000	701,310	712,890	2,545,490	2,568,110
Means	8,536	8,608	60,500	60,320	11,646	12,328	23,020	23,522	36,560	37,800	140,262	142,578	509,098	513,622
1930	5,500	5,250	40,900	39,200	9,430	5,430	16,300	12,110	31,900	23,930	104,030	85,920	399,070	363,080
1931	4,150	3,890	24,700	31,800	7,890	8,650	9,080	12,040	(22,000)	(23,000)	67,820	79,380	195,080	227,120
1932	5,350	5,580	51,500	44,100	10,900	12,100	(23,400)	(23,250)	(35,300)	(39,800)	126,450	124,830	446,550	433,270
1933	5,890	6,040	42,480	41,160	12,500	11,100	(25,700)	(23,600)	(42,300)	(39,660)	128,870	121,560	487,130	483,740
1934	4,952	4,602	21,540	27,380	7,824	9,415	(16,700)	(16,300)	(26,000)	(28,840)	77,016	86,537	227,984	236,463
5-year Totals	25,842	25,362	181,120	183,640	48,544	46,695	91,180	87,300	157,500	155,230	504,186	498,227	1,755,814	1,743,673
Means	5,168	5,072	36,224	36,728	9,709	9,339	18,236	17,460	31,500	31,046	100,837	99,645	351,163	348,735
1935	4,307	4,455	57,260	55,350	16,180	15,640	(23,500)	(23,860)	35,700	34,700	136,947	134,005	539,853	542,595
1936	4,559	4,642	47,680	46,040	13,840	13,710	(16,300)	(17,100)	(38,600)	(39,320)	120,979	120,812	280,621	286,888
1937	3,618	3,473	49,900	48,680	11,480	13,430	(24,600)	(24,250)	36,810	37,840	126,408	127,673	514,792	496,827
1938	6,010	6,306	65,520	74,540	13,170	10,677	(18,000)	(22,500)	35,720	33,980	138,420	148,003	428,880	422,997
1939	5,461	.....	58,650	......	10,900	......	(22,900)	......	32,620	......	130,531	(115,600)	442,069	(417,000
4- or 5-year Totals	23,955	18,876	279,010	224,610	65,570	53,457	105,300	87,710	179,450	145,840	653,285	646,093	2,206,215	2,166,307
Means	4,791	4,719	55,802	56,153	13,114	13,364	21,060	21,928	35,890	36,460	130,657	129,219	441,243	433,261
Record Totals	546,227	542,068	3,962,330	3,916,450	858,534	844,552	1,348,480	1,330,040	2,482,250	2,451,300	9,197,821	9,200,010	28,162,379	28,115,290
Means	8,403	8,460	60,956	61,150	13,208	13,200	20,745	20,800	38,187	38,300	141,499	141,533	433,250	432,526

Table 4, concluded--Section C, concluded [For designation of columns as numbered in parentheses see pages -]

(1)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)
1920	807.5	.706	705	.616	0.950	0.885	.658	.564	.693	.637	.743	.696	+.082	+.035	+12.4	+ 5.3
1921	508.6	.444	545	.476	0.624	0.638	.410	.445	.657	.697	.712	.746	+.051	+.085	+ 7.7	+12.9
1922	615.8	.538	622	.543	0.816	0.777	.484	.498	.593	.641	.659	.699	-.002	+.038	- 0.3	+ 5.7
1923	565.5	.494	612	.535	0.673	0.662	.459	.510	.682	.770	.734	.808	+.073	+.147	+11.0	+22.2
1924	616.1	.538	587	.513	0.674	0.691	.512	.478	.760	.692	.798	.742	+.137	+.081	+20.7	+12.2
5-year Totals	3,113.5	....	3,071	....	.....	.....	....	....	....	....	....	....	.....	.....	.....	.....
Means	622.7	.544	614.2	.537	0.747	0.731	.505	.499	.676	.683	.728	.735	+.067	+.074	+10.1	+11.2
1925	330.7	.289	377	.329	0.478	0.491	.252	.298	.527	.607	.605	.670	-.056	+.009	- 8.5	+ 1.4
1926	463.3	.405	534	.467	0.565	0.694	.374	.422	.662	.608	.717	.673	+.056	+.012	+ 8.5	+ 1.8
1927	957.6	.837	905	.791	0.947	0.841	.815	.781	.861	.929	.884	.941	+.223	+.280	+33.7	+42.3
1928	712.2	.622	696	.608	0.829	0.883	.582	.555	.702	.629	.750	.689	+.089	+.028	+13.5	+ 4.2
1929	783.0	.684	769	.672	0.946	0.919	.633	.624	.669	.679	.723	.731	+.062	+.070	+ 9.4	+10.6
5-year Totals	3,246.8	....	3,281	....	.....	.....	....	....	....	....	....	....	.....	.....	.....	.....
Means	649.4	.567	656.2	.573	0.753	0.766	.531	.536	.705	.700	.753	.748	+.092	+.087	+13.9	+13.2
1930	503.1	.440	449.0	.392	0.559	0.461	.416	.379	.744	.822	.787	.850	+.126	+.189	+19.1	+28.6
1931	262.9	.230	306.5	.268	0.364	0.426	.204	.237	.560	.556	.632	.629	-.029	-.032	- 4.4	- 4.8
1932	573.0	.501	558.1	.488	0.679	0.670	.466	.452	.686	.675	.738	.728	+.077	+.067	+11.6	+10.1
1933	616.0	.538	605.3	.529	0.692	0.653	.508	.505	.734	.773	.777	.810	+.116	+.149	+17.5	+22.5
1934	305.0	.266	323.0	.282	0.414	0.465	.238	.247	.575	.531	.643	.606	-.018	-.055	- 2.7	- 8.3
5-year Totals	2,260.0	....	2,241.9	....	.....	.....	....	....	....	....	....	....	.....	.....	.....	.....
Means	452.0	.395	448.4	.392	0.542	0.535	.366	.364	.675	.680	.729	.733	+.068	+.072	+10.3	+10.9
1935	676.8	.591	676.6	.591	0.735	0.720	.563	.566	.766	.786	.804	.821	+.143	+.160	+21.6	+24.2
1936	401.6	.351	407.7	.356	0.650	0.649	.293	.299	.451	.461	.540	.549	-.121	-.112	-18.3	-16.9
1937	641.2	.560	624.5	.546	0.679	0.686	.537	.518	.791	.755	.825	.796	+.164	+.135	+24.8	+20.4
1938	567.3	.496	571.0	.499	0.743	0.795	.448	.441	.603	.555	.668	.628	+.007	-.033	+ 1.1	- 5.0
1939	572.6	.500	(532.6)	.465	0.701	0.621	.461	.435	.658	.700	.713	.749	+.052	+.088	+ 7.9	+13.3
5-year Totals	2,859.5	....	2,812.4	....	.....	.....	....	....	....	....	....	....	.....	.....	.....	.....
Means	571.9	.500	562.5	.491	0.702	0.694	.460	.452	.655	.651	.712	.707	+.051	+.046	+ 7.7	+ 7.0
65-year Totals	37,360.2	....	37,315.3	....	.....	.....	....	....	....	....	....	....	.....	.....	.....	.....
Means	574.749	.502	574.059	.502	0.760	0.760	.452	.451	.595	.593	.661	.661	.....	.....	.....	.....
65-year mean departures, numerical values regardless of sign													±.080	±.077	±12.1	±11.6

The record of 65 water-years, from 1875 to 1939, shown in Table 4, for the five tributaries above listed, including some derivations for the earlier years at all of these stations, except Chattanooga, developed extreme ranges of +33.7 per cent and -29.9 per cent, with an average departure of ±12.1 per cent from the record mean, involving the tentative discharge-estimates at

Table 5--Derivations of river-discharges from index-areas: Comparison of departures from record means as determined for the Mississippi River at Vicksburg, Mississippi

(Y_u = Yield in csm from ungaged area; Y_g = Yield in csm from gaged area; Y_{u+g} = Yield in csm from total drainage-area; (Y_{u+g}/Y_g) = Comparison of yields, expressing the csm from total drainage in terms of csm from the gaged area)

Item	Weights accorded		Gaged area		Record included		Water-years				Calendar-years			
							Record mean	Departures, per cent			Record mean	Departures, per cent		
								Maximum		Absolute mean		Maximum		Absolute mean
No.	Ft. Benton, Montana	Keokuk, Iowa	Square miles	Per cent of total drainage	Water-years (Oct.-Sep.) ending	No.	$\left(\frac{Y_{u+g}}{Y_g}\right)$	+	-		$\left(\frac{Y_{u+g}}{Y_g}\right)$	+	-	
1	1	1	186,217	16.3	1875-1939	65	0.661	33.7	29.9	± 12.1	.661	42.3	32.1	± 11.6
2	2	2	329,817	28.8	1875-1939	65	0.728	21.9	38.2	± 12.0	.808	28.0	43.1	± 12.1
3	3	1.5	294,917	25.8	1875-1939	65	0.784	33.2	27.8	± 12.4	.783	39.0	28.4	± 12.1
4	5	2	403,617	35.3	1875-1939	65	0.858	38.5	26.0	± 11.5	.857	37.0	25.9	± 11.4
5	5	2	403,617	35.3	1875-84 and 1925-39	25	0.887	34.0	24.8	± 12.6	.879	33.6	29.7	± 13.2
6	5	2	403,617	35.3	1925-1939	15	0.988	20.3	23.2	± 12.5	.980	30.1	22.8	± 12.5
7	1	1	186,217	16.3	1925-1939	15	0.734	20.4	26.4	± 10.7	.729	38.4	24.7	± 12.7
8	1	1	186,217	16.3	1928-1939	12	0.723	14.1	25.3	± 10.0	.723	17.6	16.2	± 11.4
9	2	2	329,817	28.8	1928-1939	12	0.882	16.3	24.1	± 9.4	.868	19.1	21.1	± 11.4
10	3	1.5	294,917	25.8	1928-1939	12	0.888	17.1	24.4	± 9.1	.876	15.5	21.7	± 10.8
11	5	2	403,617	35.3	1928-1939	12	0.990	19.1	24.4	± 9.8	.980	16.3	23.0	± 12.0
	Hermann, Missouri	Keokuk, Iowa												
12	1	1	1,031,900[a]	90.2	1928-1939	12	1.12	4.5	4.5	± 2.5	....	....	....	......
13	1	1	1,031,900	90.2	Monthly means[d]	12	1.12	21.2	30.7	± 10.9	....	....	....	......
14	1	1	1,031,900	90.2	excluding Decembers	10	1.12	21.2	10.9	± 9.5	....	....	....	......
15	1	1	1,031,900	90.2	Daily discharge[b]	12	1.12	30.8	13.5	± 12.1	....	....	....	......
16	1	1	1,031,900	90.2	excluding Decembers	10	1.12	25.4	13.5	± 10.2	....	....	....	......
17	1	1	1,031,900	90.2	Daily discharge[c]	12	1.12	24.8	13.4	± 10.3	....	....	....	......
18	1	1	1,031,900	90.2	excluding Decembers	10	1.12	22.4	13.4	± 8.6	....	....	....	......

[a] Main tributaries as listed in Table 6, including also the Ohio River at Metropolis, Illinois, Arkansas River at Little Rock, Arkansas, and White River at De Valls Bluff, Arkansas.

[b] Daily discharges for the first day of each month at the tributary stations, and on the tenth day for Vicksburg, Mississippi, thus allowing nine days for transit.

[c] Daily discharges for the first day of each month at tributary stations, and on the eighth day for Vicksburg, Mississippi, thus allowing seven days for transit.

[d] October to December, 1936, and April to December, 1937.

Table 6--Discharge of Mississippi River at Vicksburg, Mississippi, as observed or as derived by the "sampling method"

(Drainage-area at Vicksburg, Mississippi, is 1,144,500 square miles)

Years of record, Oct-Sep	Drainage-basin, station, and area in square miles					Yield total gaged area, 1,031,900, cfs	Yield total ungaged area, 112,600, cfs
	Ohio River, Metropolis, Ill., 203,000, cfs	Mississippi R., Keokuk, Iowa, 119,000, cfs	Missouri River, Hermann, Missouri, 528,200, cfs	Arkansas River, Little Rock, Ark., 157,900, cfs	White River, De Valls Bluff, Ark., 23,800, cfs		
1927-28	(315,000)	63,700	(90,000)	53,100	41,200	563,000	149,200
1928-29	(346,000)	80,700	114,000	60,400	36,800	637,900	145,100
1929-30	(253,000)	40,900	55,400	26,300	23,400	401,000	102,100
1930-31	(129,000)	24,700	37,100	19,300	18,700	228,800	45,400
1931-32	(289,000)	51,500	70,300	(34,500)	21,000	466,300	106,700
1932-33	(354,000)	42,480	51,900	33,000	27,400	508,780	107,220
1933-34	(169,190)	21,540	29,750	18,740	15,630	254,850	50,150
1934-35	285,200	57,260	80,010	65,400	32,190	520,060	156,740
1935-36	226,600	47,680	41,090	14,010	10,110	339,490	62,110
1936-37	337,100	49,900	59,000	35,700	26,600	508,300	132,900
1937-38	269,800	65,520	56,640	46,590	30,140	468,690	98,610
1938-39	286,400	58,650	53,170	21,770	28,290	448,280	124,320
Totals	3,260,290	604,530	738,360	430,810	311,460	5,345,450	1,280,550
12-year Means	271,691	50,378	61,530	35,901	25,955	445,454	106,713
Totals for latest 7-year record......						3,048,450	732,050
Latest 7-year means......						435,493	104,579

Years of record, Oct-Sep	Total area, 1,144,500 square miles		Yearly yield		Ratios		Departures from latest 7-year mean			
	Yield, cfs	Y_{u+g}, csm	Gaged Y_g, csm	Ungaged Y_u, csm	$\left(\frac{Y_u}{Y_g}\right)$	$\left(\frac{Y_{u+g}}{Y_g}\right)$	$\left(\frac{Y_u}{Y_g}\right)$		$\left(\frac{Y_{u+g}}{Y_g}\right)$	
							csm	pct	csm	pct
1927-28	712,200	.622	.546	1.325	2.43	1.14	+.24	+11.0	+.02	+1.8
1928-29	783,000	.684	.618	1.289	2.09	1.11	-.10	- 4.6	-.01	-0.9
1929-30	503,100	.440	.389	0.907	2.33	1.13	+.14	+ 6.4	+.02	+1.8
1930-31	274,200	.240	.222	0.403	1.82	1.08	-.35	-16.0	-.04	-3.6
1931-32	573,000	.501	.452	0.948	2.10	1.11	-.09	- 4.1	-.01	-0.9
1932-33	616,000	.538	.493	0.952	1.93	1.09	-.26	-11.9	-.03	-2.7
1933-34	305,000	.266	.247	0.445	1.80	1.08	-.39	-17.8	-.04	-3.6
1934-35	676,800	.591	.504	1.392	2.76	1.17	+.57	+26.0	+.05	+4.5
1935-36	401,600	.351	.329	0.552	1.68	1.07	-.51	-23.3	-.05	-4.5
1936-37	641,200	.560	.493	1.180	2.39	1.14	+.20	+ 9.1	+.02	+1.8
1937-38	567,300	.496	.454	0.876	1.93	1.09	-.26	-11.9	-.03	-2.7
1938-39	572,600	.500	.434	1.104	2.54	1.15	+.35	+16.0	+.03	+2.7
Totals	6,626,000	....	....	.....	....	....	....	.....	....	....
12-year Means	552,167	.482	.432	0.948	2.19	1.12	0.00	0.0	0.00	0.0
Totals[a]	3,780,500	....	....	.....	....	....	....	.....	....	....
Means[a]	540,071	.472	.448	0.692	1.54	1.07	0.00	0.0	0.00	0.0
12-year departures, arithmetical means......							±.290	±13.2	±.029	±2.5

Notes: Parentheses () enclose derived, unofficial, or partly estimated basic data among official data. [a]For latest 7-year record.

Vicksburg as above described. The corresponding departures for the first ten years were ±12.7 per cent, -21.8 per cent, and ±11.4 per cent, showing some improvement over the 9.4 per cent index-area above noted, and shown in Table 3.

Equalizing index-area representation--It is obvious that, with three of the five index-areas in Table 4 included in the Ohio Valley, this region has much higher representation than has the Missouri River basin, or 21.0 per cent as compared with 4.7 per cent of the respective drainages.

Table 7--Tests of the "sampling method" for determining stream-discharge

(Deriving discharge from an entire drainage-basin through the observed relationship to measured yield from gaged areas during years of concurrent record)

Years of record	Drainage-basin, station, and area in square miles								
	Tenn. R., Johnsonville, Tenn., 38,510, cfs	Cumberland, Clarksville, Tenn., 16,000, cfs	Wabash, Mount Carmel, Illinois, 28,600, cfs	Kentucky River, Lockport, Kentucky, 6,310 cfs	Miami River, Hamilton, Ohio, 3,640, cfs	Scioto River, Chillicothe, Ohio, 3,850, cfs	Kanawha R., Kanawha Falls, W. Virginia, 8,367, cfs	Muskingum River, McConnelsville, Ohio, 7,411, cfs	Tygart River, Fetterman, W. Virginia 1,340, cfs
1927-28	72,300	30,300	31,500	9,060	3,280	4,110	13,300	9,150	3,070
1928-29	84,000	33,700	35,000	10,200	4,070	4,270	12,400	7,790	2,340
1929-30	59,100	20,100	29,900	4,990	3,810	4,670	9,430	7,630	1,950
1930-31	36,200	11,000	7,060	(2,850)	1,070	1,230	7,890	2,660	1,680
1931-32	72,100	29,300	25,500	(8,850)	2,930	3,650	10,900	6,330	2,420
1932-33	84,200	31,800	42,300	8,730	5,060	4,630	12,500	7,600	2,790
1933-34	46,140	20,100	8,043	5,346	1,179	883	7,824	2,879	1,887
1934-35	62,540	29,249	22,710	12,950	1,397	2,038	16,180	6,607	2,903
1935-36	61,740	18,820	14,510	8,237	2,257	2,803	13,840	7,182	2,891
1936-37	67,700	30,770	39,250	8,893	5,467	5,167	11,480	11,730	2,777
1937-38	58,330	21,860	35,020	(7,270)	4,439	3,503	13,170	8,504	2,833
1938-39	65,210	27,130	29,700	(11,100)	3,574	3,355	10,090	7,056	(2,200)
12-year Totals	769,560	304,129	320,493	98,476	38,533	40,311	139,004	85,118	29,741
Means	64,130	25,344	26,708	8,206	3,211	3,359	11,584	7,093	2,478

Years of record	Basin of Allegheny River, Red House, New York, 1,640, cfs	Yield total gaged area (57 pct) 115,667, cfs	Yield total ungaged area (43 pct) 87,333 cfs	Yield total drainage, Metropolis, Illinois, 203,000		Yield in csm		$\left(\frac{Y_u}{Y_g}\right)$	$\left(\frac{Y_{u+g}}{Y_g}\right)$	Departures from lates 5-year means	
				cfs	Y_{u+g} csm	Gaged Y_g	Ungaged Y_u			$\left(\frac{Y_u}{Y_g}\right)$ pct	$\left(\frac{Y_{u+g}}{Y_g}\right)$ pct
1927-28	3,610	179,680	135,320	(315,000)	1.553	1.553	1.549	1.00	1.00	0	0
1928-29	3,440	197,210	148,790	(346,000)	1.705	1.705	1.704	1.00	1.00	0	0
1929-30	2,680	144,260	108,740	(253,000)	1.247	1.247	1.245	1.00	1.00	0	0
1930-31	1,780	73,420	55,580	(129,000)	0.635	0.635	0.636	1.00	1.00	0	0
1931-32	2,620	164,600	124,400	(289,000)	1.423	1.423	1.424	1.00	1.00	0	0
1932-33	2,240	201,850	152,420	(354,270)	1.745	1.745	1.745	1.00	1.00	0	0
1933-34	1,858	96,139	73,051	(169,190)	0.833	0.831	0.836	1.01	1.00	0	0
1934-35	2,343	158,917	126,283	285,200	1.405	1.374	1.446	1.05	1.02	+ 5	+2
1935-36	2,571	134,851	91,749	226,600	1.116	1.166	1.051	0.901	0.957	-10	-4
1936-37	3,393	186,627	150,473	337,100	1.661	1.613	1.723	1.07	1.03	+ 7	+3
1937-38	2,665	157,594	112,206	269,800	1.329	1.362	1.285	0.943	0.976	- 6	-2
1938-39	2,210	161,625	124,775	286,400	1.411	1.397	1.429	1.02	1.01	+ 2	+1
12-year Totals	31,410	1,856,773	1,403,787	3,260,560	.....	.....	.....	....	....	+14	+6
Means	2,618	154,731	116,982	271,713	.....	.....	.....	....	....	-16	-6

Note: Parentheses () enclose derived, unofficial, or partly estimated basic data among official data.

[a] Differences between computed and observed discharges.

Various weights, ranging up to 5, were therefore given the Fort-Benton record, resulting in a somewhat closer agreement for some of the years, and wider disagreement for others. At the same time, the whole series of 65 years and also of selected portions were worked out on various bases for giving increased weight to both the Fort-Benton and Keokuk records, as a means of according better representation to the Missouri Valley and possibly to the neighboring Arkansas Valley Region.

The results are shown in Table 5, which indicate that either slight advantages or disadvantages may accrue from assigning such increased weights, and that the general scope of departures from mean relationship remains more nearly constant throughout the range of tests than would be expected (maximum departures) ranging from approximately 20 per cent to 40 per cent plus or minus, and a mean absolute of approximately 12.5 per cent even with weights as high as 5 and 2, respectively, given to the Fort-Benton and Keokuk records.

It will be noted that giving additional weights to the Fort-Benton and Keokuk records serves to reduce the quantity Y_g, or yield in csm from the gaged area, so that the corresponding values of (Y_{u+g}/Y_g) or comparison between the unit-yield from the entire basin and that of the index-areas as thus weighted, approaches the value 1.00, coming within two per cent in both items 6 and 11 of Table 5.

As a further test, the 12-year period, terminating in 1939, was analyzed in the same manner, but using the official records of the Ohio River at Metropolis, Illinois, the Mississippi River at Keokuk, Iowa, the Missouri River at Hermann, Missouri, the Arkansas River at Little Rock, Arkansas, and the White River at De Valls Bluff, Arkansas, as shown in detail in Table 6, and summarized as item 12 of Table 5. The five tributary drainage-areas above these stations aggregate 90.2 per cent of the total above Vicksburg, Mississippi, leaving only 9.8 per cent ungaged. The extreme departures are +4.5 per cent and -4.5 per cent, while the arithmetic or absolute mean is ±2.5 per cent, or about one-fifth of the departures noted for about one-fifth as much gaged area during the record period or portions thereof, or 16.3 per cent area compared with 90.2 per cent. In other words, the errors seem to reduce almost proportionately with the ungaged area.

This constitutes a notable test of the method, inasmuch as the Vicksburg record, after June 1931, is from the United States Geological Survey, and the earlier records of this tabulation resulted from a study of all available data, official or otherwise, and embodies the latest revisions to more nearly reconcile some divergent evaluations.

As only the last five years were covered by official records of the Ohio River at Metropolis, Ohio, these five years were used to establish the relationship between the yields of gaged and ungaged areas, shown in Table 6. Likewise, the earlier seven-year record of the Ohio River was derived by the same method, based on gaged areas aggregating 57.0 per cent of the total area, as shown in Table 7.

It can be observed readily, in Tables 3, 4, 6, and 7, that a better comparison is afforded by (Y_{u+g}/Y_g), or the yield of the total area compared with the yield of the gaged area, than by a direct comparison between ungaged and gaged area yields in csm (cubic feet per second per square mile), or reduced to percentage. The yield quantities of the (Y_{u+g}/Y_g)-columns are much more convergent and consistent than those of the (Y_u/Y_g)-columns, and reflect closer coordination and inherent relationship as the gaged-area percentage increases, imparting its characteristics more and more to the enveloping total drainage, but not necessarily to the ungaged portion.

The final column of Table 7 shows departures of +2, -4, +3, -2, and +1 per cent respectively for the five years of record, which are less than half of those in the next preceding column. These departures, totaling +6 per cent and -6 per cent, indicate that the gaged areas are representative of the total Ohio River drainage, insofar as annual discharge is concerned. The factor 1.00 was therefore used in Table 7 for deriving the discharge at Metropolis, Illinois, for the first seven years of this 12-year record, based on the 57 per cent gaged or index-areas as there shown.

Ordinarily, the factor (Y_{u+g}/Y_g) will be either greater or less than 1.00; if it is 1.12, for example, as in the last five items of Table 5, it indicates that the yield per square mile of the total drainage-basin is 12 per cent higher than the gaged index-area yield; or if the ungaged area, 9.8 per cent of the total, accounts for a 12 per cent increase in csm from the entire drainage, then the ungaged area must yield (12/9.8) = 122 per cent more in csm than the average for the Mississippi River Basin above Vicksburg. These average yields were given for the 12-year record in Table 6 as 0.432 and 0.948 csm respectively, with a ratio of (Y_u/Y_g) = 2.19, affording fair confirmation as well as illustrating the influence of added decimals in the computations.

Forecasting monthly and daily discharge from tributary records--In order to test the index-area relationship more adequately in the prediction of flood-discharge, as well as for monthly yield, records of the same five tributaries were used for estimating probable monthly and daily discharge at Vicksburg. Examining the 15 consecutive months from October, 1936, to December, 1937, it was found that the discharge, as derived from the records of main tributaries, showed departures intermediate between those recorded for annual discharges with gaged areas of 16.3 per cent and 90.2 per cent of the total drainage, as shown in Table 5, except as the formation or release of ice and associated storage could account for the wider variations during the winter and early spring months. For the remaining ten months, the departures had an extreme range of +21.2 per cent and -10.9 per cent from the 12-year mean shown in Table 6, while the discharges at Vicksburg on the 10th of separate months, derived from tributary discharges on the 1st of the respective months, showed corresponding maximum departures of +25.4 per cent and -13.5 per cent, with a mean of ±10.2 per cent, as shown in items 15 and 16 of Table 5.

This derivation involved comparing the tributary discharges on the 1st of each of those fifteen calendar months with the successive discharges at Vicksburg on the 1st, 3rd, 5th, 10th, and 15th days, to disclose that a fair forecast could be had of main stream-discharge during the ice-free months, provided the time of transit is taken into account. Thus, the Vicksburg daily discharges were approximated within the range above noted from the tributary discharges of some nine days earlier; results for five days either earlier or later than the 10th, would have been more widely divergent for some of the months, and practically unchanged for others, or for the 8th, in slightly closer agreement, as shown by items 17 and 18 of Table 5.

Prior use of index-areas for evaluating runoff--Within the broad concept of index-areas described under the heading "Transition to larger areas" above, in which they may consist of any representative plots, large or small, or any selected tributaries, even though they may constitute a considerable or major portion of the drainage-basin, it is known that the basic principles governing the forecasting of stream-flow, as well as evaluating flood or other runoff assemblies from some of the component parts, have long been accepted and widely used in practical fields. In varying degrees, this method has had application wherever engineers and hydrologists have recognized the fundamental laws of similitude, in the broadest technical fields.

In the course of assembling the data shown in Figure 11 in H. D. 308, Report on the Mongaup River tributary of Delaware River (H. D. No. 660, 71st Congress, 3rd session, 1931), which used essentially the same method as herein outlined but depended on graphic solutions, a number of typographical errors were discovered and corrected which had apparently remained unchallenged among official data throughout the several years following publication. These incidents proved the practical value of index-area relationships far beyond the supplying of missing data for neighboring stations.

Summary

(1) Index-area yield may give fairly reliable indications of river-discharge, provided: (a) The areas thus utilized are truly representative of the various sections, or of the dominant classifications of terrain within the drainage-basin; (b) the rainfall-pattern and distribution are taken into account through adequate station-records at well-distributed points, or provided this matter is automatically adjusted through wide distribution of many index-areas, or by reason of their extent to constitute a considerable or even a major portion of the total drainage; (c) the relationship between yield from the total drainage, as compared with that of the index-area, is developed by tests of actual runoff during several storms, seasons, or years of concurrent record; (d) the percentage of variations representing extreme departures from mean runoff-relationship may be tolerated up to about plus or minus one-third to one-half of the percentage of ungaged area, with mean departures further reduced by one-half or two-thirds; and (e) due allowance is made for the time of runoff-transit between index-areas and the gaging-station on the main river-channel, for valley or other storage and release, and for diversions associated with consumptive use.

(2) Without prejudice to the increasing volume of basic hydrologic data obtained according to the best standards, some derivations, estimates, and approximations may be developed for official gagings of tributaries as index-area data, and valuable confirmations may result for some station-records, or occasionally rectification of erroneous data may be thereby accomplished.

(3) One of the distinctive features of this approach is tacit recognition of the diversity of yields ordinarily manifest between index-areas and the total drainage-basin, making necessary the provision for expressing unit-yield from the total drainage in terms of corresponding yield from the index-areas (the quotients in the column headed (Y_{u+g}/Y_g).

(4) The generalizations derived from examination of yearly and monthly means may be directly applied in some measure to daily river-discharge, and consequently, with further limitation, to flood-peaks, if the guiding principles of flood-routing and storage-equations are strictly applied, including specific data on volumes and rates of accumulation or release of ice and associated channel- or valley-storage.

References

[1] H. R. Leach, H. L. Cook, and Robert E. Horton, Storm-flow predictions, Trans. Amer. Geophys. Union, pp. 435-446, 1933.

[2] Waldo E. Smith, Modification of the index-area principle and the anticipated application of the principle to Muskingum River flood-control, Trans. Amer. Geophys. Union, pp. 455-460, 1938.

[3] Headwaters control and use, in Report of Upstream Engineers' Conference, Chap. 3, September, 1936.

U. S. Soil Conservation Service,
Washington, D. C.

A GRAPHICAL FLOOD-ROUTING METHOD

Walter T. Wilson
(Presented by F. F. Snyder)

Introduction--This paper consists of four parts. The first part describes a method of routing floods through reservoirs by a graphical solution of the storage-equation employing a variable time conversion-factor. This time conversion-factor is the ratio of storage to discharge for a given rate of discharge. The functional relationship is expressed by a curve or by a family of loop-curves.

The second part of the paper describes an approximate method of reservoir-routing for use where the assumption of a constant time-conversion factor is adequate. It is demonstrated that a constant time-conversion factor exists when the recession-curve is logarithmic. The time-conversion factor can be evaluated by a number of methods, which are outlined.

The third part of the paper suggests a method for flood-routing in streams. This method makes use of the graphical procedure described earlier, and is based on two assumptions: (1) That an outflow-hydrograph can be obtained by weighting the translatory and the storage-components of a flood-wave in a reach, and that the relative weights are a conservative reach-characteristic; (2) that the travel-time for a wave determines the time-conversion factor for the storage-component of the reach.

The fourth part suggests a method of hydrograph-synthesis for basins. This method assumes an analogy between a basin and the reach of a stream. The surface-runoff or pluviagraph of rainfall minus losses is considered analogous to the inflow-hydrograph.

The storage-equation--Outflow equals inflow plus rate of decrease of storage. Designating I as inflow, Q as outflow, and S as rate of change of storage, all in second-feet, the storage-equation becomes $Q = (I - S)$. The expression of outflow in terms of inflow and rate of change of storage is a single equation with two unknowns, the inflow being known. It is necessary to establish a second and independent relationship. By means of two simultaneous equations the outflow can be determined. The relationship between storage and outflow may be used for this second equation. It may be convenient to recall that discharge and storage may both be expressed as functions of stage. With variable flow, the function of storage versus outflow may be represented as a family of loop-curves, each loop for a certain rate of change of outflow. However, a single-valued curve is ordinarily used and found to be adequate. Designating this time-conversion factor as T, and recognizing the fact that the ratio of cfs to cubic feet must have the dimension of time, the volume of storage in cubic feet equals T times the rate of discharge. Differentiating with respect to time, the rate of change of storage equals T times the rate of change of discharge, or $S = T(dQ/dt)$. Substituting this expression for S in the storage-equation: $Q = [I - T(dQ/dt)]$. This is the working equation for the graphical computation of outflow from an unregulated reservoir.

The procedure with variable time-conversion factor--In Figure 1, let it be assumed that the inflow-hydrograph is given as shown, and that the T-curve shows the variable time-conversion factor as a function of outflow. Point B represents both inflow and outflow at the beginning of the first time-increment. Let A represent the mean inflow for the first one-hour increment. A' is chosen by trial and error so that A' has the same ordinate as A, and so that the time-distance between A and A' equals T for the mean value of the first increment of outflow. BC represents the outflow for the first time-increment, and is so drawn that if segment BC were extended, the line would pass through point A'. This construction satisfies the working equation. The slope of BCA' is the average rate of change of outflow during the first hour, and AA' equals T. If the lines AA' and BCA' were drawn, the angle formed would have the same tangent as the angle BC makes with a horizontal line, namely, dQ/dt. The ordinate from A to the mid-point of BC equals (dQ/dt)T or (dQ/dt)T equals inflow minus average outflow, which is the working equation. The operation for the next time-increment is to locate point D, thus obtaining the ordinate of D'. Then by trial and error D' is located so that DD' equals T for the outflow-increment CE, which, if extended, would pass through D'. As with many graphical procedures, the operation is easier to perform than to describe. Frequently the points corresponding to A' and D' may be correctly located the first trial, and nearly always the second trial.

The procedure with constant time-conversion factor--The method described above need not be used except where a constant value of T is inadequate. With a constant value of T for all values of outflow, the operation involves no trial-and-error process. An (inflow + T)-curve is prepared by translating the inflow-hydrograph T units to the right. This may be done by tracing the inflow-hydrograph. All the points corresponding to A' and D' of Figure 1 will be on the (inflow + T)-curve. The procedure for the first time-increment is to locate the point on the (inflow + T)-curve having the same ordinate as the mean inflow for the first time-increment. Using the same notation as in the preceding example, locate A' on the (inflow + T)-curve, lay a straightedge across B and A' and draw BC. For the next time-increment locate D', and laying a straightedge across C and D', draw CE.

The T-curve of Figure 1 has a typical shape. In Figure 1, the solid-line outflow-hydrograph was computed on the basis of a varying T, ranging from about four to about seven hours, as shown. The dashed-line outflow-hydrograph was computed with a constant T of five hours. The closeness of these two outflow-hydrographs illustrates the adequacy of the assumption of a constant T for the example given. In actual practice, this would have to be determined empirically for each case on its own merits. This method was devised by the writer while routing floods through Yellowstone Lake, and in that particular case T was so very nearly constant that as an example, it would not show how a properly chosen constant T approximates a variable T having a range of values such as shown in Figure 1.

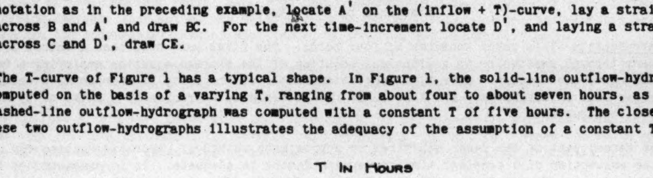


Fig. 1--Flood-routing procedure

Methods of determining T--(1) Relating the stage-storage curve for a reservoir to the stage-discharge curve of the spillway.

(2) Performing the graphical operation in a reverse manner, and getting the T-curve from the observed inflow- and outflow-hydrographs of previous floods.

(3) Trial and error with various values of T.

(4) Examination of recession-curves. In the examination of a recession-curve of outflow, it is convenient to relate the discharge at a given instant to the discharge at a later instant

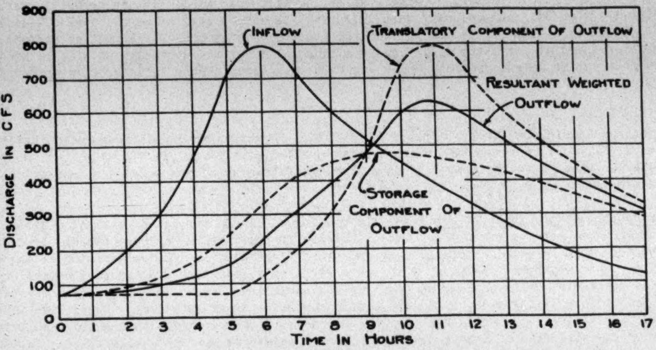


Fig. 2--Flood-routing procedure

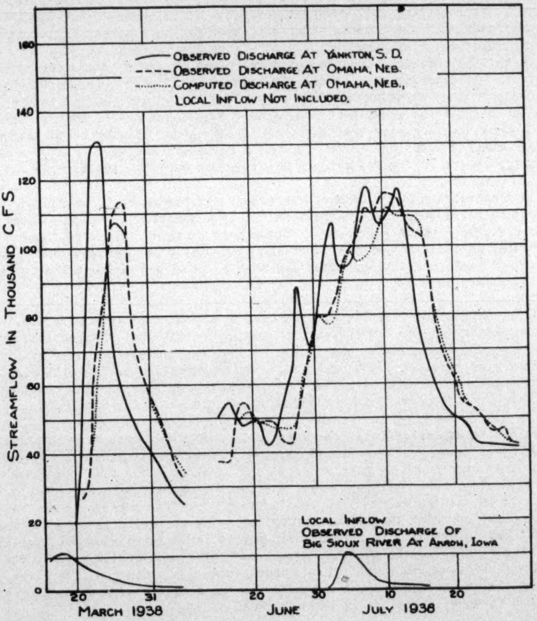


Fig. 3--Missouri River flood-routing example

by a factor C. Comparing the mean daily discharge Q_0 to the mean daily discharge for the first day following, Q_1, we have $Q_1 = C \times Q_0$. If Q_0 is 100 cfs, and if C is 0.90, Q_1 will be 90 cfs. If C remains constant, the discharge for the second day, Q_2, will be CQ_1 or C^2Q_0, and in the numerical example, Q_2 will be 81 cfs. For the nth day, with constant C, $Q_n = C^nQ_0$, which is an exponential or logarithmic recession-curve. Referring to the working equation described earlier, namely, $Q = I - T(dQ/dt)$, and assuming that inflow has ceased, I will be zero. Then Q will equal $-T(dQ/dt)$, which expresses the discharge from the reservoir as it drains. Recalling that at any point on an exponential curve the slope equals a constant times the ordinate, it will be seen that $Q = -T(dQ/dt)$ is an exponential. Equating this expression to the value of $Q_n = Q_0C^n$

$$-T(dQ/dt) = Q_0C^n$$

Integrating and solving for C, $C = e^{-1/T}$ or $T = -1/\log_e C$, which provides a means of determining T in terms of C. It is interesting to express the discharge in terms of T: $Q = Q_0e^{-n/T}$, where e is the Naperian base, n is the number of days from the beginning of the recession, and Q_0 is the initial discharge.

Routing through the reach of a stream--The routing of floods through a reach of a stream is partly analogous to reservoir-routing. The difference is that natural channel-storage produces less flattening than reservoir-storage. The amount of flattening is a characteristic of the reach and may vary anywhere from zero, with uniformly progressive flow, to the full retarding effect of a reservoir. With a sluggish reach having large overflow-volume, the reservoir-analogy is approached. In a swift reach, with very little channel-storage, uniformly progressive flow is approached. In Figure 2 the (inflow + T)-curve is the outflow-hydrograph that would result from uniformly progressive flow of travel-time T. Figure 2 shows two extreme shapes that an outflow-hydrograph may have. One extreme is the (inflow + T)-curve representing translation of the inflow-hydrograph by uniformly progressive flow. The other extreme is the outflow-hydrograph taken from Figure 1, representing full-reservoir effect. It is assumed that the actual outflow-hydrograph for any reach will lie somewhere between these two curves, shown with dashed lines in Figure 2. The resultant weighted outflow-curve of Figure 2 is an example of a case where the actual outflow is half way between these two extremes, that is, half translatory effect, and half storage-effect. To demonstrate that the time-conversion factor T is the same as the travel-time, consider Seddon's law $U = dQ/dA$, where U is wave-velocity, and (dQ/dA) is the rate of change of discharge per unit of cross-sectional area. A is taken as the average cross-sectional area. Letting L equal the length of the reach, AL is the volume of storage in the reach. Also, $U = L/T$. Equating these expressions for U, $(dQ/dA) = L/T$ and $T = L(dA/dQ)$, or T = storage divided by discharge, which is the relation used earlier in deriving the working equation.

The method suggested here is to examine the record for the reach to be routed. The travel-time, or time-conversion factor, T, may be determined by inspection or by one of the methods discussed earlier. Plot the (inflow + T)-curve. Using this (inflow + T)-curve, plot the storage-component of outflow, as described earlier. If the values of T for various rises, and the proportionate effects of storage and translation are seen to be conservative characteristics of the reach, this method is applicable.

The assumption of constant T implies the assumption of constant wave-velocity. Examination of travel-time curves for a number of streams, including the Missouri, Yellowstone, Connecticut, Tennessee, Allegheny, and Monongahela, has indicated that the travel-time does not ordinarily vary greatly over a wide range of discharge. Much of the variation occurs at low rates of discharge, and the quantity of flow occurring at low discharge-rates is so small that errors in routing this portion of a flood-wave do not seriously affect the total outflow.

It is impossible to express exactly the extremely complicated physical characteristics of a reach of a stream. All flood-routing methods involve certain simplifying assumptions. No single method exists that has been found to have universal application. The difference between flood-routing methods is in the nature of the assumptions and approximations made. The success of a method is determined by the degree to which its inherent assumptions approximate the true nature of the stream and flood to which the method is applied. The criterion is strictly empirical. The writer has not had opportunity to examine this method for a large number of cases. The example shown in Figure 3 indicates that the method does show promise for certain conditions. With the uncertainties of ungaged local inflow, bank-storage, and other difficulties, it is sometimes questionable whether an example demonstrates the adequacy of a method, or whether it is evidence of good fortune in evaluating the unknowns.

Figure 3 shows the hydrographs of the Missouri River at Yankton, South Dakota, and at Omaha, Nebraska, for the spring and summer of 1938. This example was chosen because there is practically no ungaged local inflow. The March rise resulted from an ice-jam near Bismarck, and the other part of the hydrograph is the regular rise in June resulting from melting snow in the mountains. Examination of earlier stream-flow records for the Yankton-Omaha Reach indicated a travel-time of about three days, and the storage-effect and the translatory effect were observed to have about equal weight. The computed discharge at Omaha was made on this basis. The hydrograph of the Big Sioux River at Akron, Iowa, is shown and seems to include the principal local inflow. The James River and Little Sioux River, other intervening tributaries, contributed practically no inflow. Akron, Iowa, is nearly as far upstream from Omaha as Yankton, indicating about three days' lag for the Big Sioux to Omaha. If the inflow from the Big Sioux were added with about three days' lag, to the computed outflow at Omaha, the observed discharge at Omaha will be very closely approximated.

Application to basin hydrograph-synthesis--The storage in a reservoir or the reach of a channel may be considered analogous to the surface-detention and channel-storage in a basin. Sub-surface flow, or other flow following Darcy's law that the discharge is proportional to the head, permit and even require the assumption that discharge is proportional to storage, which means a constant T. During discharge from a basin, successive portions of the basin contribute runoff. The area of the portion of the basin contributing during any time-increment may be related in a conservative way to this time-increment, and the entire basin be integrated, each portion to its successive time-increment, so that an area-time curve is determined. This area-time curve has been used by hydrologists for many years, and is sometimes described as an area-shape diagram, or it is said that use is made of time-contours. An analogy to the inflow-hydrograph may be prepared by relating this area-time curve of a basin to the pluviagraph of rainfall minus losses. The time-conversion factor, or T, may be determined by one or more of the methods described earlier. This method of hydrograph-synthesis has been used with apparent success in computing stream-flow contribution from snow-melt.

This method, in assuming a constant T, is subject to the same criticism as the unit-graph method, that is, in using the same time-base for all values of storm-intensities. However, a curve of T versus discharge might be determined, and a proper value of T used for each storm, depending upon the intensity of the storm. This method avoids one of the objections to the unit-graph method, namely, that a logarithmic recession-curve may more nearly represent the true picture of a unit-storm hydrograph than a constant length of time-base for all storm-intensities.

In connection with area-shape diagrams and the conception of a conservative lag-time for a basin, reference is made to the paper by F. F. Snyder, "Synthetic unit-graphs" [Trans. Amer. Geophys. Union, Part I, p. 447, 1938]. The idea of weighting the storage and translatory effects in flood-routing is not new, a reference to an application of this principle being the mimeographed bulletin by Gerald T. McCarthy, "The unit hydrograph and flood routing" [U. S. Eng. Office, Providence, Rhode Island, June 24, 1938, revised March 21, 1939]. A recent reference to a graphical method, using the relationship of storage versus outflow, is a paper by R. S. Goodridge, "A graphical method of routing floods through reservoirs" [Trans. Amer. Geophys. Union, Part II, p. 433, 1937]. An example and discussion of logarithmic recession-curves in natural channels is given in a paper by B. S. Barnes, "Flood forecasting in the Upper Mississippi Valley" [Bull. 20, Univ. Iowa, Proc. Hydraulic Conf., March 1940].

While no attempt is made to list the growing list of contributors to flood-routing technique, the following additional references should be mentioned: Harold A. Thomas, "The hydraulics of flood movements in rivers," an Engineering Bulletin of Carnegie Institute of Technology, Pittsburgh, Pennsylvania, 1937; Ing. Dr. A. Schoklitsch, "Hydraulic structures," a text and handbook, volume 1, published by the American Society of Mechanical Engineers, New York City, 1937; R. E. Horton, "Determining the regulating effect of a storage-reservoir" [Eng. News-Record, v. 81, No. 10, p. 455, 1918]; L. G. Puls, of the United States Engineer Office, Chattanooga District, originated a flood-routing method bearing his name, and which is described in the bulletin "Engineering construction--Flood control," The Engineer School, Fort Belvoir, Virginia, 1940.

U. S. Weather Bureau,
Washington, D. C.

DISCUSSION

W. B. LANGBEIN (U. S. Geological Survey, Washington, D. C.; communicated)--Sherman Woodward in 1920 described a practical method for routing of floods which he devised for application to the design of the flood-control dams of the Miami Conservancy District. The intensified flood-control program of more recent years has again inspired many to devise new methods for the more rapid solution of the storage-equation, with particular application to reservoirs. The method proposed by Mr. Wilson ranks high among these and has merits that entitle it to consideration. It is rigorously correct for ideal reservoirs, that is, those with truly level surfaces. Applied to natural channels it has no advantage save that of expediency. All routing methods in general engineering use are approximations, since the complexities of natural river-channels and the mathematical difficulties make the problem insuperable. In general the practical methods vary in accuracy to the degree to which the volume of storage is approximated. The McCarthy method expresses the storage in terms of the weighted inflow to, and the outflow from, a reach. The weight-factor also determines the attenuation of the flood-wave. It is noted that the author suggests that the attenuation be determined by routing a "storage-component" as though the reach were a reservoir and the translating component, and drawing the actual graph in between the two. No method is given for determining the exact amount of attenuation between these two limits, so that this important problem still remains unsolved. Other questions to be answered are: (1) Does the "storage-component" represent the greatest possible amount of attenuation to be obtained from a given volume of storage? (2) Can the discharge increase after passage through a reach without increments? The latter question is important on western streams.

In describing methods of evaluating T, it might be added that its value equals the time-interval between centers of mass of inflow and outflow regardless of the shape of the respective graphs. This subject was developed by the writer in a recent paper [W. B. Langbein, Some channel-storage and unit-hydrograph studies, Trans. Amer. Geophys. Union, pp. 620-627, 1940].

AMERICAN GEOPHYSICAL UNION

TWENTY-SECOND ANNUAL MEETING

APRIL 30 - MAY 3, 1941

SECTION OF HYDROLOGY

REPORTS

WASHINGTON, D. C.
MAY 1, 2, 3, 1941

CONTENTS

REPORTS, PERMANENT RESEARCH-COMMITTEES, SECTION OF HYDROLOGY

Page

First Session, 9 a.m., May 1, 1941

Committee on the Chemistry of Natural Waters, 1940-41. C. S. HOWARD, Chairman. 901

Special Committee on Flood-Waves, 1940-41. LORENZ G. STRAUB, Chairman. 901

Committee on Dynamics of Streams, 1940-41. LORENZ G. STRAUB, Chairman. 903
  Appendix A--Sub-Committee on Land-Forms. IRVING B. CROSBY, Chairman. 904

Committee on Transpiration and Evaporation, 1940-41. JOSEPH KITTREDGE, Chairman. 906

Committee on Physical Limnology. T. C. ADAMS, Chairman 916

Second Session, 2 p.m., May 1, 1941

Committee on Physics of Soil-Moisture, 1940-41. N. E. EDLEFSEN, Chairman 917
  Some thermodynamic aspects of the use of soil-moisture by plants. N. E. EDLEFSEN . . . 917
    Discussion. WILLIAM A. BECK, S. C. BROOKS, HAROLD H. CLUM, R. H. COTTON, A. S. CRAFTS, H. C. EYSTER, W. GARDNER, G. A. GREATHOUSE, R. E. HORTON, M. R. HUBERTY, A. R. JORDAN, P. J. KRAMER, M. R. LEWIS, B. E. LIVINGSTON, W. F. LOEHWING, W. E. LOOMIS, E. C. MILLER, O. W. MONSON, G. W. MUSGRAVE, M. L. NICHOLS, G. J. PEIRCE, H. L. SHANTZ, HILDA F. ROSENE, B. T. SHAW, F. J. VEIHMEYER, F. W. WENT, P. R. WHITE, and N. E. EDLEFSEN 926

Committee on Infiltration, 1940-41. G. W. MUSGRAVE, Chairman 941

Committee on Rainfall, 1940-41. MERRILL BERNARD, Chairman. 944

Coordinating Committee on Hydrology between the American Society of Agricultural Engineers and the American Geophysical Union, 1940-41. H. S. RIESBOL, Chairman 946

Committee on Underground Waters, 1940-41. DAVID G. THOMPSON, Chairman. 948
  Appendix A--Research on hydrology and physiography of limestone terranes. A. C. SWINNERTON. 950

Third Session, 9 a.m., May 2, 1941

Committee on Snow, 1940-41. J. E. CHURCH, Chairman 953
  Appendix A--List of current publications on snow and ice. CARL ELGES, RALPH W. BURHOE, and L. JACCHIA. 981

Committee on Glaciers, 1940-41. FRANCOIS E. MATTHES, Chairman. 1006

Advisory Committee on Soil Conservation Research, 1940-41. R. E. HORTON, Chairman. . . . 1012
  Supplement. M. L. NICHOLS. 1013

Committee on Runoff, 1940-41. W. G. HOYT, Chairman 1014
  Appendix A--Summary of hydrologic research data being collected at experimental areas, watersheds, forests, and demonstration-projects maintained by Federal agencies. W. G. HOYT, in cooperation with J. M. DAVIDSON, I. H. SIMS, MERRILL BERNARD, GAIL A. HATHAWAY, and others 1016

Session of 9 a.m., May 3, 1941

Notes on joint round-table on runoff and infiltration. W. G. HOYT, Chairman, Committee on Runoff, and G. W. MUSGRAVE, Chairman, Committee on Infiltration. 1027

Research-Committee of Eastern Snow-Conference. G. A. HATHAWAY, CARROLL F. MERRIAM (Chairman), and J. SWEET. 1029

Index of names, Part III. 1030

Index of subjects, Part III 1032

REPORTS, PERMANENT RESEARCH-COMMITTEES, SECTION OF HYDROLOGY

NATIONAL ACADEMY - RESEARCH COUNCIL BUILDING
FIRST SESSION, 9:00 A.M., MAY 1, 1941

REPORT OF COMMITTEE ON THE CHEMISTRY OF NATURAL WATERS, 1940-41

C. S. Howard, Chairman

The membership of the Committee during the past year was as follows: I. A. Dennison, Bureau of Standards; C. S. Scofield, Department of Agriculture; D. G. Thompson, Geological Survey; T. G. Thompson, University of Washington, Seattle, Washington; and C. S. Howard, United States Geological Survey, Washington, D. C. (Chairman).

Doctor Dennison has continued his studies on the corrosion of metals and has prepared, for publication by the National Bureau of Standards, certain information concerning field-tests of natural resistance to corrosion. This report indicates the effect of various elements used as alloys. The tests have not yet been sufficiently comprehensive to furnish a discussion of the relation between the chemical composition of materials under the test and their behavior in various environments.

Mr. Scofield prepared a paper which was published in the Journal of Agricultural Research in July, 1940, entitled, "Salt balance in irrigated areas." Mr. Scofield, in this paper, discusses the "salt balance" in irrigated areas with specific reference to irrigated areas in the Rio Grande in New Mexico and Texas, and one area on the Colorado River in Arizona. Observations were made to determine (1) what proportion of the irrigation-input must be allocated to root-zone leaching in order to prevent the accumulation of soluble salts in the soil of the root-zone and (2) what proportion of the dissolved salts contained in the irrigation-water is removed from solution by the crop-plant (alfalfa) or by the soil.

The field-studies conducted under the Pecos River Joint Investigation of the National Resources Planning Board and other agencies were completed in 1940. One of the major problems in the Pecos Basin is the high salinity of the ground- and surface-waters used for irrigation. The programs of the various agencies were concerned with the following factors:

(1) Determination of the loads of dissolved solids carried by the Pecos River at different points in the Basin
(2) Determination of the sources of the dissolved solids picked up by the River
(3) Plans for utilizing the highly concentrated waters with the least harmful effect on crops
(4) Plans for reducing the loads of dissolved solids carried by the River.

The available data show that the Pecos River carried 48,300 tons of dissolved solids in 64,430 acre-feet of water at Santa Rosa, New Mexico, and 687,000 tons of dissolved solids in 98,340 acre-feet of water at Red Bluff, New Mexico, in the year ending September 30, 1940. This increase of over 600,000 tons in this stretch of the River represents the salinity-problems of the irrigated areas in this stretch of river and in areas below the Red Bluff Station. The results of the investigation are to be published by the National Resources Planning Board.

U. S. Geological Survey,
Washington, D. C.

REPORT OF SPECIAL COMMITTEE ON FLOOD-WAVES, 1940-41

Lorenz G. Straub, Chairman

The Special Committee on Flood-Waves was created four years ago with the purpose of stimulating activity in the study of various types of wave-phenomena. Several Sub-Committees were originally appointed with a view of bringing up-to-date a resume of the literature on the subject of waves and recording the work in progress by various Federal, State, and private agencies. The results of these studies and a number of others by individual persons have been published in the Transactions of the American Geophysical Union for the past three years.

The Committee on Flood-Waves remains the same as in the past year. The membership is as follows: Merrill Bernard, U. S. Weather Bureau, Washington, D. C.; M. C. Boyer, United States Geological Survey, Washington, D. C.; H. N. Eaton, Hydraulic Laboratory, National Bureau of

Standards, Washington, D. C.; R. S. Goodridge, United States Soil Conservation Servation Service, Washington, D. C.; G. A. Hathaway, Office of Chief of Engineers, United States Engineer Department, Washington, D. C.; Robert E. Horton, Consulting Hydraulic Engineer, Voorheesville, New York; Ivan E. Houk, United States Bureau of Reclamation, 440 Customhouse, Denver, Colorado; Hans Kramer, United States Engineer Office, Panama Canal; F. T. Mavis, College of Engineering, Pennsylvania State College, State College, Pennsylvania; M. P. O'Brien, College of Engineering, University of California, Berkeley, California; Lorenz G. Straub (Chairman), University of Minnesota, Minneapolis, Minnesota; and H. A. Thomas, Carnegie Institute of Technology, Pittsburgh, Pennsylvania.

Last year the Committee sponsored the preparation and publication of a paper by Professor Harold A. Thomas on "Graphical integration of the flood-wave equations".

This year the effort of the Committee has been directed primarily in the stimulation of the preparation of papers by persons whose field of activity includes particularly the study of waves. Specifically, there is presented on the Section's program May 1, 1941, a paper by B. R. Gilcrest and L. E. Marsh on "Channel-storage and discharge-relations in the Lower Ohio River Valley". There are also on this year's program other papers which relate to the field of activity of the Committee on Flood-Waves. These are sponsored by other Committees of the Section.

University of Minnesota,
Minneapolis, Minnesota

REPORT OF COMMITTEE ON DYNAMICS OF STREAMS, 1940-41

Lorenz G. Straub, Chairman

The Committee on Dynamics of Streams has continued during the past year without change in membership. For the most part, the activities of the Committee have been the results of work of individual members. There has been one active Sub-Committee, a report of which is presented as a part of the program of this year's annual meeting. This is a Sub-Committee on Land-Forms.

The complete membership of the Dynamics of Streams Committee is as follows: K. Hilding Beij, National Hydraulic Laboratory, United States Bureau of Standards, Washington, D. C.; H. H. Bennett, Director, United States Soil Conservation Service, Washington, D. C.; Irving B. Crosby, Consulting Geologist, 6 Beacon Street, Boston, Massachusetts; John B. Drisko, 34 West Baltimore Street, Kensington, Maryland; H. V. Geib, Division of Research, United States Soil Conservation Service, College Station, Texas; C. S. Howard, Chemist, United States Geological Survey, Washington, D. C.; E. W. Lane, Iowa Institute of Hydraulic Research, University of Iowa, Iowa City, Iowa; W. C. Krumbein, Department of Geology, University of Chicago, Chicago, Illinois; L. M. Lawson, American Commissioner, International Boundary Commission, First National Bank Building, El Paso, Texas; W. C. Lowdermilk, United States Soil Conservation Service, Washington, D. C.; Gerard H. Matthes, Mississippi River Commission, Box 363, Vicksburg, Mississippi; G. W. Musgrave, United States Soil Conservation Service, Washington, D. C.; Martin E. Nelson, Engineer, United States Engineer Sub-Office, Iowa Institute of Hydraulic Research, University of Iowa, Iowa City, Iowa; M. P. O'Brien, College of Engineering, University of California, Berkeley, California; R. L. Parshall, Colorado State College, Fort Collins, Colorado; G. W. Pickels, Department of Civil Engineering, University of Illinois, Urbana, Illinois; C. H. Pierce, Senior Engineer, U. S. Geological Survey, Washington, D. C.; C. E. Ramser, Watershed and Hydrologic Studies, United States Soil Conservation Service, Washington, D. C.; William W. Rubey, United States Geological Survey, Washington, D. C.; Fred C. Scobey, United States Department of Agriculture, Room 219 P. O. Building, Berkeley, California; Lorenz G. Straub (Chairman), University of Minnesota, Minneapolis, Minnesota; Roy N. Towl, Consulting Engineer, 506 South Fifty-seventh Street, Omaha, Nebraska; A. C. Trowbridge, Department of Geology, University of Iowa, Iowa City, Iowa; Herbert D. Vogel, Fort Belvoir, Virginia; H. H. Wheaton, Department of Mathematics, Fresno State College, Fresno, California; and N. E. Winters, State Agricultural College, Stillwater, Oklahoma.

It has been customary for the Committee to present periodically a review of literature appearing in various countries within the scope of the Committee's activities. Although a detailed review is not presented at this time, a preliminary study of articles available indicates a definite retardation of progress in research in stream-dynamics in most countries outside of the United States.

A valuable group of papers which were presented in the field of erosion and sediment-transportation by rivers at the International Hydrology Conference held in Washington September, 1939, have not yet been published, although most of the manuscript had been set up in type at the time of the meeting. The publication was to have been issued in Paris early in 1940, immediately following the meeting. Some of the papers of this Conference were reviewed briefly in last year's report of the Committee on Dynamics of Streams. Another meeting which was affected by international tension was that of the International Association for Hydraulic Structures Research scheduled to be held in September, 1939, in Liege, Belgium. A number of papers on stream-dynamics were scheduled for presentation on this occasion. Contrary to the Washington International Meeting, the Liege meeting was cancelled, but the papers were published in Stockholm, Sweden, a few months ago.

Activity in America thus far has continued without apparent retardation in any of the fields of the Committee. Progress has been steady, particularly in problems dealing with mechanics of sediment-transportation by flowing water. At the meeting of the American Geophysical Union in 1940 the following papers were presented which are pertinent to the work of this Committee: Erosional land-slope-profile shape in terms of the erosive power of rainfall-runoff, by James M. Little; A criterion for instability of flow in steep channels, by G. H. Keulegan and G. W. Patterson; A rating-curve method for determining silt-discharge of streams, by F. B. Campbell and H. A. Bauder; A study of sedimentation in a Miami Conservancy District Reservoir, by E. W. Lane and J. C. Kennedy; Suspended-material transportation under non-equilibrium conditions, by A. A. Kalinske; Determination of Manning's n from vertical-velocity curves, by W. B. Langbein; A distinction between bed-load and suspended load in natural streams, by H. A. Einstein, Alvin G. Anderson, and Joe W. Johnson; and The different approaches to the study of propulsion of granular materials and the value of their coordination, by Paul Nemenyi.

The continued and even accelerated interest of workers throughout the country in the field of stream-dynamics on special problems having to do with transportation of sediment by rivers and over land-surfaces last year, led to the sponsoring by the Committee on Dynamics of Streams of a Symposium on Sediment-Transportation. Seven papers on the program for May 1, 1941, are particularly related to the behavior of rivers in consequence of sediment-movement due to various factors, many of which are still not clearly defined.

There are still many phenomena of river-behavior as influenced by turbulence and resulting sediment-transportations which are subject to controversy, even by close observers. Thus, controversies are found within the ranks of this Research-Committee regarding points of vital importance. However, as compared to the situation a few decades ago--even a few years ago--the agreement of observers and theoretical analysts on many stream-dynamics phenomena involving sediment-transportation is very good. Many of the diametrically opposite opinions of the past have been completely eliminated and dispute resolves itself usually as to details of explanation of occurrences, the general nature of which is usually agreed upon.

University of Minnesota,
Minneapolis, Minnesota.

APPENDIX A--SUB-COMMITTEE ON LAND-FORMS

Irving B. Crosby, Chairman

The Sub-Committee on Land-Forms of the Committee on Dynamics of Streams of the American Geophysical Union has had, since its inception, as its principal, but not sole subject of study, the causes and controlling factors of stream-meanders. Members of the Committee and their colleagues have been supervising studies on this and related problems. Now an extensive investigation on the fundamentals of stream-meandering is under way.

GERARD H. MATTHES, a member of the Committee, reports that an investigation is under way at the United States Waterways Experiment Station of the Mississippi River Commission aimed at determining the fundamental laws that govern the meandering of rivers in erodible beds. Model studies are being conducted. The materials used in the model to date are composed of coal-particles. It is expected later to use other materials possessing greater cohesion. The series of tests now under way will endeavor to establish the function of each of the several variables which operate in this complex phenomenon. Five variables have been set up whose effects are being studied singly and in combination: (1) Valley-slope; (2) bed-load; (3) discharge; (4) bed-resistance; (5) transverse oscillation. A paper on the "Basic aspects of stream-meandering" has been prepared by Mr. Matthes and is to be presented at the annual meeting of the Union, May 1941. In this paper the importance of these variables is discussed and the preliminary results of this investigation are described.

Mr. Matthes is also directing office studies of the literature on the subject of stream-meanders. It is requested that reference to articles on the subject be sent to him at the office of the Mississippi River Commission at Vicksburg, Mississippi.

The study of channel-stability in the lower Mississippi River, begun two years ago under the supervision of Mr. Matthes and reported in 1940, has been continued. It is conducted with special reference to evidences of aggrading or degrading of the bed and the bearing which artificial features such as bank-revetments and levee-confinement have had thereon.

By the direction of General M. C. TYLER, President of the Mississippi River Commission, field-tests are being undertaken in the Mississippi River with recently perfected echo-sounding apparatus as part of a program of under-water studies aimed at determining (1) the rate of bed-load movement in the Mississippi River, (2) the changes in bed-configuration that take place during rising and falling stages, respectively, and (3) the rate of movement of sand-waves, which in the Mississippi River attain extraordinarily large sizes. It has been found that no system of ordinary soundings will satisfactorily develop the shape of such sand-waves. It is believed that echo-soundings will be peculiarly adapted to developing the precise configuration of sand-waves and will also determine their rate of movement. The immediate object of these various field-tests is to gain a clear understanding of those aspects of shoaling, scouring, and bank-caving which are of importance to engineers in everyday river hydraulics practice. It is felt that the results also will constitute a major contribution to the knowledge of river-morphology.

Studies of other subjects in the general field of the Committee have been undertaken at the Iowa Institute of Hydraulic Research under the general supervision of Professor E. W. LANE, a member of the Committee. These include a study to improve the methods and apparatus of measuring the sediment-load of streams, particularly the suspended sediments. Two reports, "Field practice and equipment used in sampling suspended sediments" and "Equipment used for sampling bed-load and bed-material", have been issued and three more are expected in the near future. Studies have been carried on at the Institute in connection with the War Department on the pulsation of large rivers. There is also being carried on, under the direction of Professor Kalinske, an experimental study of the transportation of sediment in an open channel. Dr. Nemenyi is compiling a bibliography of work in the field of stream-forms. There was completed during the year, under the direction of Professor Lane, a comparison of Lacey's stable-channel relations with conditions in the St. Clair and Lower Mississippi rivers. The agreement of these streams with Lacey's relations was found not to be very close.

At the St. Anthony Falls' Hydraulic Laboratory of the University of Minnesota the following studies are being carried out under the supervision of Professor LORENZ G. STRAUB, Chairmen of the Committee on Dynamics of Streams and ex-officio member of this Sub-Committee on Land-Forms:

A study is being conducted in the laboratory on the influence of fluid turbulence upon the transportation of bed-sediment. The experimental set-up involves a re-circulating system and heating coils for varying the temperature and, therefore, viscosity of the fluid. Sand is fed into the channel at the upstream end by an electrically operated elevator. Observations are made of velocity-distribution and character of bed-load movements. The controllable variables are the rate of sand-feed, the viscosity of the fluid, and the rate of water-flow.

Another study involves the effect of channel-contraction works such as might be used, for example, in improvements of navigation, upon equilibrium-conditions on the stream-bottom. These studies are being made with a movable bed consisting of sand. Part of the total length of the channel is contracted and observations are made for different bed-loads and water-discharges of the equilibrium-conformation of the stream-bottom and of the slope of the water-surface.

A further experimental study on which considerable information has already been collected involves the sedimentation at the confluence of rivers. Idealized model streams are allowed to approach each other at different angles and the equilibrium-formation at the confluence is studied. The variables involved include the bed-load and water discharge of the main stream and also of the tributary. These studies in particular have been sponsored by the Committee on Hydraulic Research of the American Society of Civil Engineers.

Still other studies are under way on hydraulic structures, such as soil-saving dams, by the United States Soil Conservation Service. These involve, in part, the investigation of methods of overcoming harmful erosion.

A recent article by ROBERT E. BATES, entitled "Geomorphic history of the Kickapoo Region, Wisconsin" and published in the Bulletin of the Geological Society of America [v. 5, No. 6, pp. 819-882], discusses meandering streams at length and gives many examples.

The various studies now being conducted under the supervision of members of the Committee and their colleagues will be continued and reported when conclusions have been reached.

6 Beacon Street,
Boston, Massachusetts

REPORT OF COMMITTEE ON TRANSPIRATION AND EVAPORATION, 1940-41

Joseph Kittredge, Chairman
(Presented by W. E. Davis)

The membership of the Committee includes the following: T. C. Adams; N. W. Cummings; W. E. Davis; S. T. Harding; A. H. Hendrickson; I. E. Houk; E. W. Lane; C. H. Lee; C. G. Rossby; T. Saville; C. A. Taylor; C. W. Thornthwaite; H. C. Troxell; H. G. Wilm; and J. Kittredge (Chairman).

Several reports of developments have become available during the year. Evaporation from snow near Fraser, Colorado, according to the first season's records by the Rocky Mountain Forest and Range Experiment Station, amounted to 3.5 inches of water, of which almost 80 per cent was lost during April and May. Interception of 30 per cent of the summer's precipitation by a lodgepole-pine forest is reported in a separate paper.

A pine-plantation, 28 years old, near Berkeley, California, intercepted an average of 20 per cent of the seasonal precipitation over a five-year period, as reported from the California Agricultural Experiment Station. Under the shade and litter-mulch of this plantation, evaporation from the soil, determined by sampling trenched plots, amounted to 0.53 inch compared with 0.78 inch from bare soil in the open during the 85 days of dry weather following May 22, 1939. Standard Weather Bureau pans in the corresponding locations gave 6.0 and 21.5 inches, respectively. From the same source, evaporation from the snow at feet elevation of 5,500 in the watershed of the Stanislaus River on the west slope of the Sierra-Nevada, over three winters averaged 0.007 inch per 24 hours. Wide variations were found in different situations and in different years.

A paper by Montgomery [see 24 of "References" at end of paper], gives a detailed analysis of the relation between vertical humidity-gradient, wind-velocity, rate of evaporation, and the hydrodynamic character of the water-surface. The author hopes that the studies will eventually make possible the calculation of the rate of evaporation by measurements of water- and air-temperatures, and wind-velocity and humidity at a single height. The equations for evaporation from hydrodynamically smooth and rough sea-surfaces are derived.

The author's analyses can be summarized by his equation for rate of evaporation

$$E = \rho k \gamma \tau (q_s - q_b) W_a$$

where ρ is the air-density, k is the universal turbulence-constant, q_s is the specific humidity of saturation with respect to the sea-surface, q_b is the humidity at height b, W_a is the wind-speed at height a, and γ and τ are so-called resistance- and evaporation-coefficients, of which theoretically the product is constant.

The experimental data presented verify in general the theoretical deductions, although it was found that the neglect of thermal stability in the derivations was not always permissible.

A study of natural water-losses from selected river drainage-basins in the humid and semi-arid regions east of the Rocky Mountains, published by the United States Geological Survey as Water-Supply Paper 846 [34], is an outstanding accomplishment of the year. Determinations of annual rainfall, annual runoff, and water-loss were made from approximately 200 drainage-areas with an aggregate period of record of over 2,000 years. The areas were sufficiently widespread to permit preparation of a map of the United States showing generalized lines of equal annual water-loss. The results indicate a definite relation between average annual water-loss and average annual temperature. A further contribution to this subject applying to mountain watersheds of the Pacific Coast has been made by Lee who computes annual water-losses from the watersheds of the San Joaquin, Kings, and Kaweah rivers in the Sierra Nevada Mountains of California. [Paper presented at meeting of South Pacific Coast Area, Section of Hydrology at Sacramento, January 17, 1941, by Charles H. Lee, published in Transactions of 1941, pp. 50-66.]

Interception by prairie-grasses, weeds, and crop-plants in Nebraska, under simulated rainfall, varied with intensity of rainfall, density of foliage, wind-movement, clearness of sky, and environmental conditions, from 20 to 70 per cent of the rainfall, according to Clark [5-a]. Annual losses of water due to interception were concluded to be as high in certain grass-lands as in adjacent forested areas.

Experiments on the effect of freeboard on evaporation from "Class-A" land-pans were conducted by R. W. REVELL at the University of Iowa in the summer of 1939. Two 48-inch pans were set up at the Iowa City Climatological Station and the water in each was maintained at a constant level by apparatus operating on the Mariotte-flask principle. Freeboards of two inches on one pan and three inches on the other were maintained, this being the range of fluctuation permitted by the Weather Bureau. Analysis of the data indicated that more evaporation occurred with a three-inch freeboard than with a two-inch freeboard at high wind-velocities. At low velocities the reverse was true. These tendencies practically balanced each other during the period of observation, indicating that the standard practice of allowing the water-level to fluctuate through a range of one inch does not produce an important error.

The value of determinations of transpiration from tanks or lysimeters as a measure or index of transpiration from comparable vegetation and soil was made the subject of further study. The same questionnaire, used by the Committee and of which the results were reported last year [10], was sent to all who were known to have had experience with this problem. Thirty-seven replies were received.

The percentages of affirmative opinion on the different questions are contained in the following summary. However, it should be noted that more of those who are not represented in the percentages are doubtful then contrary-minded.

(1) The prospect of useful results for hydrology from experimentation on transpiration from vegetation in containers is sufficient to justify continuation, 91 per cent.

(2) There is a difference between rates of transpiration for the same soil and vegetation grown inside and outside of containers, 65 per cent.

(3) The prospect of useful results for hydrology from experimentation on transpiration from vegetation in containers is sufficient to justify expansion, 62 per cent.

(4) A usable relationship can be derived to correct results from containers to make them applicable to natural conditions, 57 per cent.

(5) The difference between rates of transpiration for the same soil and vegetation grown inside and outside of containers can be made negligible by: (a) Surrounding the containers with the same vegetation, 72 per cent; (b) insulating or burying the containers, 63 per cent; (c) increasing the size of the containers to exceed the depth of root-penetration, 60 per cent; (d) providing for drainage as in lysimeters, 58 per cent; (e) improvement in technique, 58 per cent; (f) increasing the size of the containers and hence the ratio of volume to surface, 57 per cent; (g) using natural soil-cores or blocks, 51 per cent.

(6) The transpiration from plants in containers is greater than that for the same soil and vegetation outside of containers, 53 per cent.

(7) The difference between rates of transpiration from the same soil and vegetation grown inside and outside of containers is not small enough to be negligible, 51 per cent.

(8) Reliable values for transpiration per unit-of-foliage, or growth, can be obtained from plants in containers, 46 per cent.

(9) Relative values as between species are reliable, 41 per cent.

If the Committee reports of last year and this report seem discouraging in regard to the value of results from tanks and lysimeters, it is not the intention of the Committee to throw cold water on projects already started or in process of completion. The value of experimentation of this kind for some purposes is appreciated. However, the danger of using quantitative values for transpiration from vegetation in containers for the estimation of transpiration from surrounding watershed-areas should be recognized. It seems clear from the answers to the questionnaire reported herewith that this application should be made only with the greatest caution, and, if possible, some check should be obtained by other methods.

While the emphasis has been on transpiration, it is, of course, obvious that what is being measured in containers with growing plants is consumptive use--a combination of transpiration and evaporation except in those instances where evaporation is eliminated by the use of a covering over the soil-surface.

In attempting to generalize from the answers to the questionnaire the point is emphasized by several that the transpiration from plants within containers would be the same as that without, if all the conditions, and particularly the soil-moisture, were the same within as without. There is, however, a serious question in the minds of many who have had experience, whether such identity of conditions within and without has been obtained in experimentation so far done. If the conditions are not thus identical, the application of figures for estimation of transpiration over large areas forthwith becomes subject to uncertainty.

There is another aspect of the data on transpiration obtained from lysimeters that may be mentioned incidentally. The factors of evapo-transpiration, precipitation, surface-runoff, and percolation, which are measured in a lysimeter-installation, comprise a cycle which can be represented by an equation. If the transpiration-factor in that equation is too large then, inevitably, some other factor, usually percolation, will be too small in a compensating amount. Thus questions concerning the reliability of results from lysimeters for the estimation of transpiration involve also other considerations.

On the whole, the uncertainty and lack of agreement evident in the replies, even among those who have had experience, clearly indicate that, for unanimous answers to the questions posed, much additional study will be required.

Illuminating comments by many who returned the questionnaire are included in the following more or less abbreviated quotations.

J. T. AUTEN (Central States Forest Experiment Station)--The size of container necessary will depend on the kind of soil and character of the plants to be grown. The problem of lateral capillarity always arises in tanks. It seems to me the finer the soil the larger the tank should be because of the distance through which capillarity acts. In a coarse sand, for instance, it probably would not matter whether the tank was 10 by 10 by 10 feet or 5 by 5 by 5 feet. The use of tanks depends largely on their being surrounded by the same sheltering conditions as natural vegetation. A block of soil never is the same in another combination of surroundings. I think the technique is all right, but the soil is part of its environment. For instance, it would be useless to take a forest soil-block out into an open field for evaporation-studies even though the technique be perfect.

R. W. BAILEY (Intermountain Forest and Range Experiment Station)--We feel that vegetation grown inside the containers should transpire somewhat more moisture than plants grown naturally. This opinion is based on the premise that all containers, because of interphase phenomenon, retain more moisture in the soil-profile and thus make possible the development of more extensive root-systems and more complete utilization of the available soil-moisture.

Providing drainage in lysimeters cannot be expected to overcome the "perched water-table effect" because of the practical impossibility of overcoming the interphase phenomena.

Notwithstanding the known limitations of lysimeter-methods it is felt that a reasonably accurate relationship of transpiration-losses from plants in containers and under natural conditions can be developed. Supplementary soil-moisture determinations on comparable sites under field-conditions should permit a rough check of the degree of accuracy obtained.

Lysi-phytometers are costly both as to equipment and time. Moreover, they will continue to be costly in terms of inconclusive results unless research is continued far enough definitely to determine the extent to which lysi-phytometer records are useful. Thus far it appears there is no proved better way for measuring transpiration in the field.

H. K. BARROWS (Mass. Institute of Technology)--Apparently temperature is one of the most important factors affecting transpiration-needs of vegetation and any departure in this respect from the tank-experiments as compared with vegetation growing naturally in the field might tend to make some difference in results [1]. Whether this difference is negligible we have no means of knowing, and I can see no way except rather indirectly to check up transpiration-uses of water [2].

C. G. BATES (Lake States Forest Experiment Station)--The most important aspect of all transpiration and water-use "tests" is the clearly established fact that both water-use and growth vary directly with the amount of water available--within the possible limits of use--and, therefore, that there can be no "fixed" or permanent relations of time, growth, leaf-area, or what-not to transpiration.

Whether or not the growth, general functioning, and transpiration of plants in small containers or large lysimeters are indicative of similar performances of natural vegetation depends on how closely all the conditions of the natural environment are duplicated in the controlled environment. It always seems more probable that such duplication will be accomplished by use of a large container better than by use of a small one, although this perhaps is not necessarily so. At least, if we employ a large lysimeter we can, except at the margins where the wall necessarily intervenes, set up a community with its competition and interaction between individuals. We can also express results in terms of ground-area. In nature, we do not say a certain tree or plant receives 30 inches of precipitation per annum; we say the acre on which it stands receives that amount, and know little or nothing as to what the individual gets along with. But what it receives, and what it uses, is not as much a function of its own leaf-area, as of the character of its neighbors and their effect on the environment. I am convinced we can do nothing for hydrology by the study of individual plants or such small groups that they do not in any sense control their environment.

Of the various factors which must be kept "natural," the above would clearly imply that water-supply was of prime importance. How rain is received and held, or whether artificial watering is done both within and without the controlled area, are possibly not more important than questions of soil-drainage, as affected by depth and other conditions. The physical importance of soil-blocks is probably overemphasized. Still, it cannot be ignored that if the soil-horizons are mixed, the root-development of the plant may be quite abnormal, as well as the location of the water-supply as affected by differential retentiveness of the layers.

H. F. BLANEY (Division of Irrigation, Soil Conservation Service)--Experiments with a tule tank set in a swamp of tules growing naturally, and a tule tank located on an adjacent bank, gave some rather interesting results [5]. In the evapo-transpiration investigations on the Rio Grande, all of our native vegetation and agricultural-crop tanks were placed in a natural environment, and I believe the results are applicable to field-conditions [31].

Current studies in San Luis Rey Valley, California, and Carlsbad, New Mexico, indicate that tanks six feet in diameter and six feet deep are satisfactory in determining the consumptive use of water for willows and saltcedars where the water-table varies from two to four feet below the surface. The results in connection with the Pecos River Joint Investigation, in saltcedar, sacaton, and salt grass--using a Mariotte control-supply tank--are also proving to be satisfactory.

F. E. CLEMENTS (Carnegie Institution of Washington)--Plants grown in containers are usually smaller than plants grown in soil outside containers, due to restriction of soil-volume. Small plants tend to transpire more rapidly per unit leaf-surface than large ones. Unfortunately, it appears that there can never be any accurate way of measuring transpiration in the field, but there can be useful approximations [6, 18, 19, 20].

R. C. COLLISON (New York State Agricultural Experiment Station)--Lysimeters with no provision for water-table maintenance are not at all comparable with field-conditions on account of excessive drying out [7, 8, 9].

E. A. COLMAN (California Forest and Range Experiment Station)--If lysimeters are understood to be buried water-tight containers provided with runoff- and seepage-outlets but with no facilities for artificially draining the soil to its in situ normal moisture-capacity, then I should say that the transpiration-rates inside and outside the lysimeters would be different. The reason is to be found in the comparison between the normal moisture-capacity of the lysimeter-block and that of the soil in its undisturbed condition. Within impervious walls, with a soil-air interface at the drainage-point, the soil-block will hold more water, perhaps through even a six-foot depth, than would the same soil-block in its natural position in the ground.

Assuming a crop inside and outside the lysimeter having roots penetrating well through the respective soil-blocks, at the start of the heavy transpiration-season, both soil-blocks hold their maximum amounts of water against the force of gravity. Due to the interface in the lysimeter, the amount of water within it is greater than that in the soil outside. Veihmeyer [32] has shown that as the soil-moisture decreases, plants can remove water from the soil with about equal facility until the moisture comes very close to the wilting-point. On this basis we could assume that transpiration-rates inside and outside would be about equal until the wilting-point was approached. However, the rate of uptake of water may depend somewhat upon the adequacy of aeration of the roots, and some of the roots, some of the time, will be in nearly saturated soil in which air-movement is greatly impeded and pressure of oxygen is low. Therefore, we might expect a lower transpiration-rate inside than outside, at least during the early part of the active transpiration-season.

Assuming for simplicity that the two transpiration-rates are equal, the greater volume of water inside the lysimeter would result in the soil outside reaching the wilting-point first. From this time until the soil inside had reached the wilting-point, the plants inside should show the higher transpiration-rate.

Buried or thermally insulated containers would aid in reducing the differences in transpiration-rates but such precautions would not equalize the soil-water relationships inside and out.

I do not believe that natural soil-cores, placed in water-tight containers, would help matters for the fundamental problem caused by the drainage-conditions of the containers would remain. However, a block of soil, either placed by filling a pit dug in the ground, or simply marked off on the surface with no disturbance to the natural soil below, would obviate the difficulty of drainage. If the controlled soil is surrounded by soil of the same kind, so that there is no textural change to cause an abnormal moisture-equilibrium after drainage, the soil within the block should have the same moisture-relationships as the untouched natural soil outside. Of course such a lysimeter is not as susceptible to close study as a block held in a tight container, but I feel that by continuous moisture-sampling and a knowledge of the moisture-energy relationships, this type of lysimeter will yield data most nearly representative of natural soil-conditions. The only lysimeters of this kind of which I am aware are the five "unconfined" lysimeters on the San Dimas Experimental Forest, although probably all permanent moisture-sampling plots might be classed with these.

The difference between rate of transpiration for the same soil and vegetation grown inside and outside of containers cannot be made negligible by increasing the depth of the containers to exceed the depth of root-penetration, because the San Dimas lysimeters' moisture-data indicate, as would be expected, that the drainage-interface of ordinary lysimeters can influence the soil-water relation through any practical depth of soil. If the drainage-point of a lysimeter were below the reach of plant-roots, the water below the ends of the roots would not be taken up by plants in place, but since the soil-moisture there would be considerably above the normal moisture-capacity due to the soil-air interface below, part of this water would be able to rise to the root-zone by capillary action as the water in the root-zone was depleted. The extent of this action would depend on many factors but would certainly not contribute to the naturalness of the lysimeter-data.

The ordinary lysimeter-drainage, consisting as it does of a soil-air interface or a soil-to-sand and sand-to-air connection, will result in the kinds of soil-moisture relations discussed earlier. Recently, however, Wallihan inserted a porous-cup tensiometer in the drainage-hole of a small lysimeter and maintained a tension of ten cm of mercury on it to facilitate drainage. He found, on comparing transpiration-loss from this one with that from one having an ordinary soil-air interface at the drainage-point, that the former showed a lower transpiration water-loss, which could be accounted for by the smaller amount of available water present. He also noted greater drainage and a decrease in anaerobic conditions in the former soil. This study, though only preliminary, is suggestive of possible means for improving the quality of lysimeter-data [27, 29, 33].

HAROLD CONKLING (California State Division of Water Resources)--The most satisfactory values on overall transpiration and other losses are obtained from measurements of stream-discharge above and below an area [5, Part II). By measurement of evaporation the data found in this way can be used for other similar areas. This method can also be applied to other areas where it is possible to measure water entering and leaving, such as the Southern California and San Joaquin valleys. Values derived from tank-experiments [5, Part I] when applied to individual crops raised in upper Santa Ana and San Gabriel valleys give results that check well with results found by the overall method of measuring inflow and outflow, indicating the accuracy of both methods. The tank-method is the only method possible in many cases and in others it is valuable to determine the losses from each type of vegetation in the area on which a mass-determination of loss has been made [5].

C. K. COOPERRIDER (Southwestern Forest and Range Experiment Station)--The subject brings to mind so many things; among these are the much-to-do about the separation of transpiration- and evaporation-losses and the comparisons of the effect of different species and kinds of vegetation, with regard to which these questions might be asked: Is it necessary to separate accurately evaporation and transpiration? Can this be done, except through relative values? Are not relative values usually adequate? The desire to reach perfection in measurement-taking sometimes seems to cause us to lose sight of the limitations governing the application of the results of measurements and to center interest in the means of making measurements, rather than in the value of the measurement when taken.

Experiencing difficulty in taking measurements may be helpful if it forces us to ask ourselves what application would be made of the results of some measurement, and hence is the measurement really necessary. For example, in attempting to measure the influence of vegetation on water-yield, I have experienced difficulty in comparing transpiration-losses of different shrubs and of shrubs and grasses. The effect of such things as differences in character and size of root-systems and the relation of parts of plants above and below the ground-surface were involved; and also the question of how much grass in nature equals the crown-spread of some shrub. However, cans with no vegetation showed evaporation to be so great an influence that it overshadowed the small differences in transpiration of different shrubs. Comparison of values obtained for cans with shrubs, with grass, and some with no vegetation, clearly indicated the desirable kinds and combinations of plants. The management necessary to bring about a trend toward that condition of vegetation was known. So relative values told us what we wished to know. Furthermore, had actual values been determined, no more would have been known about how to manage the land.

No single type of installation will ever give all the answers, and the lysimeter should neither be considered a cure-all or be discarded because it fails to be the cure-all. When properly adapted to some particular use and then fitted into the scheme of things, as a link in a chain of investigations, the lysimeter is a valuable instrument. Like most such instruments, on the other hand, it may be dangerous--at least the results and the interpretation of the meaning of results may be dangerous.

JOHN S. COTTON (Federal Power Commission)--I have made plans for surrounding large-size blocks of earth with concrete. In a sloping lysimeter with a porous slab at the lower end for drainage, the lines of drainage through the soil are not uniform, resulting in different times for drainage from different parts and different degrees of wetness. An improved design would provide a porous concrete slab the whole length of the lysimeter. The lines of drainage would then be uniform, the times of drainage and degrees of wetness the same.

F. L. DULEY (Soil Conservation Service) and T. A. KIESSELBACH (University of Nebraska)--Relative values may be fairly reliable, but we must keep in mind the difference likely to be obtained from lysimeters having controlled and constant moisture-supplies and results actually occurring in the field where some species may exhaust the total water more than others. The hydrologist is more interested in the total water and depth of water a crop or forest may remove from the soil than he is in the rate of transpiration or transpiration-ratios.

This question of transpiration has been given a great deal of study during the last half-century by soils men, and plant physiologists. Unless the hydrologists have some real reason to believe that they can enter this field of study and get information that the research men already in the fields have overlooked, there is little justification for the attempt.

It is our opinion that the results already obtained are sufficiently accurate for the use of hydrologists insofar as they are likely to be able to use them.

Numerous results have been obtained to show that the transpiration-ratio may vary between wide limits, depending upon environmental conditions. It has also been shown that the total amount of water a crop may remove may also vary between wide limits depending upon the amount of available water actually in the soil to be transpired.

Since we already know that these wide variations do occur depending on conditions, there is much question whether additional studies having as their object the more accurate determination of transpiration for a given set of environmental conditions would add much to the working knowledge of hydrologists.

Soils men have pretty much abandoned further efforts in this field of research, thinking that they could more profitably use their efforts in other directions. This fact might be considered seriously by the hydrologists before they spend too much time or money on this old subject [15, 16].

B. A. HENDRICKS (Southwestern Forest and Range Experiment Station)--In working with small lysimeters and containers, we have found that the natural rainfall is not sufficient to keep the plants alive during the spring and fall dry periods and that a small amount of watering is necessary. Under natural conditions, plants are less restricted as to space, can penetrate to deeper depths, and have a greater amount of soil-moisture available to them.

There are indications that soil-temperatures are slightly higher in containers and that growth may take place a little earlier, causing slightly more rapid transpiration in containers than under natural conditions. This can be overcome to some extent by surrounding the containers with vegetation. We have found that plants grown in containers and surrounded by tall grass lost less water than plants in containers located in a bare area.

I believe that the greatest improvement can be obtained by simulating natural conditions as to size of plants, spacing, litter-covering, and soil-conditions.

The most usable relationship, if natural conditions are properly simulated, would probably be that of surface-areas occupied by plants in containers and in the field.

In hydrological investigations many useful results, other than relative transpiration of different plant-species, may be obtained by the use of lysimeter- or tank-studies. For example, the time and duration of highest water-use by plants and its relation to time and amount of precipitation has an important effect on water-yield in the Southwest. When the greater portion of fall, spring, and winter precipitation falls in mid-winter when transpiration-draft is negligible, water-yield is much greater than is the case when a large part of the precipitation falls in early fall and late spring when transpiration is greater.

G. H. HICKOX (Tennessee Valley Authority)--The subject of lysimeters as a measure of transpiration is not fundamentally different from that of evaporation from water-surfaces in that the energy-relationships of thermodynamics must be satisfied in both cases. It is probable that the use of energy in the case of plant-life is not well understood, and it may be that energy is stored within the plant in a way which could not occur with inorganic materials. However, the total energy-input to a lysimeter and the vegetation contained in it must be accounted for by various forms of energy-output, such as heat-transmission by conduction, convection, or radiation, evaporation of water, or storage [14].

H. O. HILL (Blackland Soil and Water Conservation Experiment Station)--Results from lysimeters at this station (Temple, Texas) indicate that approximately 50 per cent of the rainfall is disposed of as evaporation and that 5 to 20 per cent is disposed of as transpiration. The crops were corn and grass. Lysimeter-results are, in general, not consistent.

HELMUT KOHNKE (Soil Conservation Service)--The use of tensiometers to facilitate drainage from lysimeters, as pointed out by Wallihan [33] may be quite valuable. The difficulty remains to establish what energy-gradient would have existed in the natural soil at the depth corresponding to the bottom of the lysimeters.

I believe that lysimeters become more valuable (representing natural conditions more closely) the larger they are both in area and depth.

For hydrologic studies, carefully designed monolith lysimeters seem to be indispensable [17].

C. H. LEE (Consulting engineer, San Francisco, California)--In dwelling upon the need for similarity of soil-conditions, the equally important aspect of meteorological exposure, including not alone relative temperatures, but also relative exposures should not be neglected. In an isolated tank the sides, as well as the top, of a stand of vegetation are exposed to conditions favoring active transpiration. The area of exposure for a small tank may be more than double that of a field-stand of the same projected area. Although not as great for a large tank, the difference is nevertheless appreciable. On the other hand, vegetation in a tank closely surrounded by an extensive similar stand has the same exposure as the field-stand. Differences in exposure of vegetation in tanks and in large stands involve not alone relative air-temperature, the surrounding vapor-blanket, and the freedom of air-movement, but also the relative area of direct exposure to the Sun, as a source of energy. Goudey's recent work in correlating rate of algal growth with ultra-violet radiation, rather than with air- or water-temperatures, is of great interest in this connection, and suggests a factor that may affect both transpiration and evaporation [13].

H. J. LOUGHEAD (Appalachian Forest Experiment Station)--A limited amount of careful study with lysimeters is a good thing and fully justified. Other methods of approach such as soil-moisture sampling and the analysis of hydrographs from small watersheds I believe offer the best possibilities for reliable results.

H. J. LUTZ (Yale University)--Transpiration-losses from plants grown in containers indicate only the losses under the specialized conditions which exist in the experimental set-up. In my judgment, conditions (particularly moisture-conditions) in containers are usually somewhat different than the conditions found in nature. Soil in containers may, in the course of a growing season, at times have higher moisture-content and at other times it is conceivable that it may be lower than in its natural state. I believe that by using relatively large masses of soil-in-place, it is possible to obtain information on the probable magnitude of transpiration. Information so obtained will, in my opinion, be sufficiently precise for practical needs [21].

A. F. MEYER (Hydraulic engineer, Minneapolis, Minnesota)--I believe there is real need for determination of transpiration from plants growing in containers under properly controlled conditions, comparing yields of stalk and seed with yields of surrounding field similarly exposed as to temperature, precipitation, and wind. Such determinations would serve as a guide to field transpiration-losses.

Containers should be large enough to permit the maintenance of conditions of soil-moisture and temperature as nearly as possible the same as in adjacent fields. This means that containers should be set in the ground and surrounded with the same vegetation. The moisture used by the plants should be correlated with the stalk- and seed-yield, which in turn should be compared with the yield in the surrounding field. If practicable, the soil-surface should be covered with a plastic that would prevent soil-evaporation, and moisture-conditions should be maintained as closely as possible equal to the actual moisture in the surrounding field. Soils should be as nearly as possible identical because of the effect of mineral constituents in the soil on the relation between water-consumption and dry matter produced by the plant.

I believe the errors remaining in well-controlled direct observations of evapo-transpiration are not excessive as compared with such determinations based on measured water-losses from cut branches, and other methods. Everything possible should be done to improve the technique, for example, placing containers so as to be surrounded by the same vegetation, using ample size and depth and providing for drainage, securing some measure of evaporation from soil through use of fallow-lysimeter with controlled drainage. Containers should be buried or insulated.

I suggest for consideration the possibility of measuring transpiration by enclosing plants with glass of type permitting penetration of normal light-rays and maintaining air-circulation, measuring volume of air and moisture-input to housing and output from housing.

Measurements should be made of evapo-transpiration losses from marshy areas with standing water and heavy growth of reeds or cattails and similar vegetation growing on large areas bordering lakes.

Changes between water-intake and water vaporized from plants during a 24-hour period do not vitiate results of lysimeter-measurements.

E. N. MUNNS (United States Forest Service)--One factor has been constantly overlooked by most of those working with transpiration, and that is that the amount of water used may be a function of soil-fertility. If there is one big weakness in most lysimeter-studies it lies in this fact.

G. W. MUSGRAVE (Soil Conservation Service)--In the vast majority of work which has been done, the best we can say usually is that the results are relative and approximate. This does not mean that they are worthless. On the contrary, to know whether transpiration of one species is greater or less than that of another, or whether a changed soil-structure or added plant-food modifies transpiration, is obviously worthwhile. The danger, however, seems to me to lie in the too complete acceptance of quantitative values as being absolute and precise.

Much can be done toward improving technique, particularly along the lines indicated by your questionnaire. Personally, I prefer not to attempt to segregate transpiration from evaporation in a cropped container but to compare them in separate replicated series, each as nearly natural as possible.

Probably there will always be difficulty in segregating evaporation and transpiration since new variables are introduced with technique required for segregation--for example, paraffin on soil-surface introduces new complexities. However, vapor-losses are commonly so great as to overshadow many minor variables and also so great as to warrant far more research than has yet been given this problem. Thus at Clarinda, Iowa, during three years and seven months, the combined evaporation and transpiration exceeded 75 per cent of the total precipitation for the same period. In this work conditions closely simulated those of nature [25, 26].

O. R. NEAL (Soil Conservation Experiment Station, Clarinda, Iowa)--My statements are based largely on observations of plants grown in lysimeters which contain soil of undisturbed structure and on which free-runoff and drainage are permitted [25]. Even under these conditions, there is a tendency for water to be held in the lower part of the soil-column [27]. If this region of increased moisture is within the root-range, an increase in transpiration over that from plants in normal soil would be expected. A similar condition would be expected in any container filled with soil.

On the lysimeters at Clarinda, Iowa, the moisture-loss in vapor-form under corn has amounted to approximately 75 per cent of the annual precipitation [26]. Under blue-grass the vapor-loss has been from 90 to 95 per cent of the precipitation.

If suitable apparatus becomes available for determining the amount, availability, and movement of moisture in undisturbed field-soil, it is possible that experimentation on transpiration can best be done in the field rather than on soil in lysimeters or other containers. Recent reports indicate progress in the development of such apparatus.

A. M. PIPER (United States Geological Survey)--Fundamentally, it seems that plants of a given species grown inside and outside containers should have identical transpiration-rates, provided the crowns are equally exposed to meteorological variables and moisture-conditions within the root-zone are identical. The latter provision is, perhaps, the more difficult to satisfy experimentally. Suspended capillary fringes seem to develop along all surfaces of contact between a container and the soil-column; excess water will not escape until the capacity of these fringes is largely or completely satisfied. Thus, if the root-zone is to have moisture-conditions comparable to those in the field, the ratio of volume to surface for the soil-column should be large. Within the soil-column of a small container, aeration may be less free than in the field. Finally, the specific retention of a soil may range widely within distances of a few feet or a few inches; thus a single container, even one of large size, may fall short of duplicating the average retention of a field.

L. A. RICHARDS (United States Regional Salinity Laboratory, Riverside, California)--Transpiration-measurements on plants grown in containers should be reliable if plant-growth conditions can be obtained comparable to natural state. This is difficult and generally not accomplished, I believe [29].

P. B. ROWE (California Forest and Range Experiment Station)--The procedures mentioned to minimize the difference are all good practices and would undoubtedly serve to lessen transpiration-differences between soils in and out of tanks. I believe that the reliability and applica- of the results of tank-studies to natural conditions could be materially increased by increasing the depth of the tanks to exceed the depth of root-penetration and capillary rise, or by providing the tanks with a small continuous soil-column, possibly extending to a fixed water-level in the collector-tank and deep enough to absorb and carry the water normally retained in the soil-blocks beyond the reach of the tank-vegetation.

F. J. VEIHMEYER (University of California)--Plants grown in containers may give some idea as to their behavior under different soil-conditions; but it is hazardous to assume that the same total quantity of water would be used by similar plants in the field if the comparison is made on the basis of water per unit-area of soil.

Cotton plants in tanks, although smaller than outside, used 47 per cent more water than the plants growing in the field [3]. Alfalfa in tanks used 83 inches and only about 50 per cent of that amount outside.

E. F. WALLIHAN (Cornell University)--In answering that transpiration from plants in containers is greater, I refer to the transpiration-rate over a long period of time when a natural soil may have had opportunities to reach the wilting-percentage. However, there probably would be a difference at any one time since plants grow abnormally in lysimeters.

Since plants growing in tanks receive different amounts of water and nutrients than those grown in natural soils, they undoubtedly have varying transpiration-rates on any basis.

J. E. WEAVER (University of Nebraska)--I have used large containers in measuring transpiration plus surface soil-evaporation in the field over a period of 20 years. I think the best index that we have of plant-behavior is growth and yield.

In our work with alfalfa and with the water-usage of various prairie- and pasture-grasses, we have always used open containers and they have always been placed under approximately normal field-conditions. The approximation is so close that no differences in growth were observed, with the native grasses, at least, inside and outside of the containers. If growth and yield are the same, I am satisfied that transpiration-rates and other plant-activities must be approximately the same [12, 28].

Certainly this method--use of large containers--is far superior to that of sampling the soil directly because there are so many losses beginning with interception, continuing through runoff, and ending with percolation beyond the root-system. I am not at all discouraged with their use, and expect to continue it rather vigorously the coming season.

H. G. WILM (Rocky Mountain Forest and Range Experiment Station)--I think it will doubtless always be impossible to obtain results from lysimeters which are quantitatively applicable to larger areas. It is beginning to be recognized now, though, that this is true of most experimental data, and that the best we can ordinarily hope for are significant differences between treatments or conditions. The thing to strive for, then, is simulation of natural conditions, so as to avoid artificial effects as far as possible. This means large, well-drained lysimeters, extending well below the root-zone. Natural soil-blocks would be desirable, except that they are inherently so variable as to obscure all except conspicuous treatment differences unless numerous replications are employed.

A. A. YOUNG (Soil Conservation Service)--As a rule, vegetation in tanks entirely surrounded and shaded by similar vegetation, transpires approximately the same as vegetation outside the tank. Exposure to wind and Sun is alike both in the tank and without. I believe that short grasses in tanks use about the same amount of water as the same grass in the field [3, 4, 5, 31, 35, 36].

References

[1] H. K. Barrows, Effect of temperature upon different reactions, J. Boston Soc. Civ. Eng., pp. 57-77, April, 1937.

[2] H. K. Barrows, Water power engineering, McGraw-Hill Book Company, 734 pp. (p. 99), 1927.

[3] S. H. Beckett and C. F. Dunshee, Water requirement of cotton on sandy loam soils in the Southern San Joaquin Valley, California, Agric. Exp. Sta. Bull. 537, 48 pp., 1932.

[4] H. F. Blaney, C. A. Taylor, and A. A. Young, Rainfall penetration and consumptive use of water in Santa Ana River Valley and Coastal Plain, Calif. State Dept. of Pub. Works, Div. Water Resources Bull. 33, 162 pp., 1930.

[5] H. F. Blaney and H. C. Troxell, Water losses under natural conditions, Calif. State Div. Water Resources Bull. 44, 176 pp., 1933.

[5a] O. R. Clark, Interception of rainfall by prairie grasses, weeds, and certain crop plants, Ecol. Monog., v. 10, No. 2, pp. 243-277, 1940.

[6] F. E. Clements and E. V. Martin, Effect of soil temperature on transpiration in *Helianthus annuus*, Plant Physiol., v. 9, pp. 619-630, 1934.

[7] R. C. Collison, Lysimeter investigations: IV. Water movement, soil temperatures, and root activity under apple trees, N. Y. Agric. Exp. Sta. Tech. Bull. 237, 31 pp., 1935.

[8] R. C. Collison, H. G. Beattie, and J. D. Harlan, Lysimeter investigations: III. Mineral and water relations and final nitrogen balance in legume and non-legume crop rotations for a period of 16 years, N. Y. Agric. Exp. Sta. Tech. Bull. 212, 81 pp., 1933.

[9] R. C. Collison and J. E. Mensching, Lysimeter investigations: I. Nitrogen and water relations of crops in legume and non-legume rotations, N. Y. Agric. Exp. Sta. Tech. Bull. 166, 99 pp., 1930.
[10] Committee on evaporation and transpiration, Report for 1939-40, Trans. Amer. Geophys. Union, Part II, pp. 406-409, 1940.
[11] E. B. Deeter and P. L. Hopkins, Progress report of the Blackland Soil and Water Conservation Experiment Station, Temple, Texas, 1931-36, 66 pp., 1938.
[12] M. T. Fredrickson, Comparison of the environment and certain physiological activities of alfalfa and prairie vegetation, Amer. Midland Naturalist, v. 20, No. 3, pp. 641-681, 1938.
[13] R. F. Goudey, Sun ray counts save sulphate, Eng. News-Rec., v. 124, No. 15, pp. 525-527, 1940.
[14] G. H. Hickox, Evaporation from a limited free water surface, Thesis for Ph.D. degree, Univ. Calif., 256 pp., ms., 1939.
[15] T. A. Kiesselbach, Transpiration as a factor in crop production, Nebraska Res. Bull. 6, 214 pp., 1915.
[16] T. A. Kiesselbach, Varietal, cultural, and seasonal effects upon the water requirements of crops, Proc. Internat. Cong. Plant Sci., v. 1, pp. 87-105, 1929.
[17] H. Kohnke, F. R. Dreibelbis, and J. M. Davidson, A survey and discussion of lysimeters and a bibliography on their construction and performance, U. S. Dept. Agric. Misc. Pub. 372, 68 pp., 1940.
[18] E. V. Martin, Effect of soil moisture on growth and transpiration in Helianthus annuus, Plant Physiol., v. 15, pp. 449-466, 1940.
[19] E. V. Martin, Effect of solar radiation on transpiration of Helianthus annuus, Plant Physiol., v. 10, pp. 341-354, 1935.
[20] E. V. Martin and F. E. Clements, Studies of the effect of artificial wind on growth and transpiration in Helianthus annuus, Plant Physiol., v. 10, pp. 613-636, 1935.
[21] N. A. Maximov, The plant in relation to water, McMillan Company, 451 pp., 1929.
[22] E. C. Miller, Bibliography on transpiration, in Plant Physiology, Second Edition, pp. 506-522, 1938.
[23] M. F. Miller and F. L. Duley, The effect of a varying moisture supply upon the development and composition of the maize plant at different periods of growth, Mo. Agric. Exp. Sta. Res. Bull. 76, 36 pp., 1925.
[24] R. B. Montgomery, Observations of vertical humidity distribution above the ocean surface and their relation to evaporation, Papers in Phys. Oceanog. Meteorol., Mass. Inst. Tech. and Woods Hole Oceanogr. Inst., v. 7, No. 4, 30 pp., 1940.
[25] G. W. Musgrave, A device for measuring precipitation waters lost from the soil as surface runoff, percolation, evaporation, and transpiration, Soil Sci., v. 40, No. 5, pp. 391-401, 1935.
[26] G. W. Musgrave and O. R. Neal, Rainfall and relative losses in various forms, Trans. Amer. Geophys. Union, Part II, pp. 349-355, 1937.
[27] O. R. Neal, L. A. Richards, and M. B. Russell, Observations on moisture conditions in lysimeters, Soil Sci. Soc. Proc., v. 2, pp. 35-44, 1937.
[28] W. C. Noll, Environment and physiological activities of winter wheat and prairie during extreme drought, Ecol., v. 20, No. 4, pp. 429-505, 1939.
[29] L. A. Richards, O. R. Neal, and M. B. Russell, Observations on moisture conditions in lysimeters, II, Proc. Soil Sci. Soc. Amer., v. 4, pp. 55-59, 1939.
[30] A. Schoklitsch, Hydraulic structures, trans. by S. Schulits, v. I and II, 1937.
[31] U. S. Nat. Res. Com., Water Res. Com., Part 6, The Rio Grande joint investigation in the Upper Rio Grande Basin in Colorado, New Mexico and Texas, 1936-37, Washington, D. C., 2 vol., 566 pp., 1938.
[32] F. J. Veihmeyer and A. H. Hendrickson, Soil moisture conditions in relation to plant growth, Plant Physiol., v. 2, pp. 71-82, 1927.
[33] E. F. Wallihan, An improvement in lysimeter design, J. Amer. Soc. Agronomy, v. 32, No. 5, pp. 395-404, 1940.
[34] G. R. Williams and others, Natural water loss in selected drainage basins, U. S. Geol. Surv., W.-S. Paper 846, 62 pp., 1940.
[35] A. A. Young, Use of water by native vegetation: Economic and engineering phases of flood control, water and soil conservation, and protection of watersheds in Southern California, Santa Maria Valley Water Conserv. Dist., pp. 168-175, Mimeo., 1939.
[36] A. A. Young and H. F. Blaney, Use of water by native vegetation, Manuscript submitted to the Div. of Irrigation, Soil Conserv. Ser., U. S. Dept. Agric. for publication as a Tech. Bull., 1941.

University of California,
Berkeley, California

REPORT OF COMMITTEE ON PHYSICAL LIMNOLOGY

T. C. Adams, Chairman

No manuscript or abstract of this report, which was presented by title, was received.

University of Utah,
Salt Lake City, Utah

REPORTS, PERMANENT RESEARCH-COMMITTEES, SECTION OF HYDROLOGY

NATIONAL ACADEMY - RESEARCH COUNCIL BUILDING
SECOND SESSION, 2:00 P.M., MAY 1, 1941

REPORT OF COMMITTEE ON PHYSICS OF SOIL-MOISTURE, 1940-41

N. E. Edlefsen, Chairman

The following members constitute the Committee: Dr. F. J. Alway, University of Minnesota, University Farm, St. Paul, Minnesota; Dr. L. D. Baver, North Carolina State College, Raleigh, North Carolina; Dr. G. B. Bodman, University of California, Berkeley, California; Dr. Richard Bradfield, Cornell University, Ithaca, New York; S. J. Buchanan, United States Waterways Experiment Station, Vicksburg, Mississippi; Dr. T. F. Buehrer, University of Arizona, Tucson, Arizona; Dr. I. A. Denison, National Bureau of Standards, United States Department of Commerce, Washington, D. C.; Dr. Willard Gardner, Utah Experiment Station, Logan, Utah; Dr. Glennon Gilboy, Massachusetts Institute of Technology, Cambridge, Massachusetts; Dr. O. W. Israelsen, Utah State Agricultural College, Logan, Utah; Dr. L. B. Olmstead, Bureau of Plant Industry, United States Department of Agriculture, Washington, D. C.; Dr. L. A. Richards, Bureau of Plant Industry, United States Department of Agriculture, Riverside, California; Dr. F. J. Veihmeyer, University of California, Davis, California; E. A. Willis, Bureau of Public Roads, United States Department of Agriculture, Washington, D. C.; and Dr. N. E. Edlefsen, University of California, Davis, California.

The annual report of the Committee this year, as has been the custom in the past, is intended to be a symposium on some aspect of the physics of soil-moisture. The Chairman took the responsibility of preparing a paper which could serve as a nucleus of the report. The idea back of the paper was to stimulate discussion on the subject. The paper was sent to each member of the Committee, and to a selected list of individuals interested in soils, and to another group of plant physiologists, with a request for their comments, opinions, and criticisms, together with their references to pertinent data. The original paper, as well as the comments and discussions by various individuals following the paper, are published herewith verbatim without being edited in any way by the Chairman. In a few replies, the discussion was part of a letter, and, in these cases, the Chairman has taken the liberty of deleting parts of the letter not pertinent to the discussion.

SOME THERMODYNAMIC ASPECTS OF THE USE OF SOIL-MOISTURE BY PLANTS

N. E. Edlefsen

In studying the literature on the use of soil-moisture by plants, one realizes that the language of the soil scientist is not the language of the plant physiologist.

Those interested in soils discuss soil-moisture in a language composed, on the one hand, of names given to the results of tests made on soils by some arbitrary measurement (for example, the moisture-equivalent, the hygroscopic coefficient, and the maximum capillary capacity) and, on the other hand, of terms perhaps more elemental or basic, such as capillary potential, pressure-potential, transmission-function, and vapor-pressure. Both types of terms describe the state of the moisture under given conditions and have been useful in developing our knowledge of soil-moisture.

The plant physiologists, however, use such terms as root-pressure, transpiration-pull, exudation-pressure, suction pressure, suction force, transpiring power, absorbing power, suction tension, turgor pressure, and diffusion-tension, some of which are of course synonymous for describing the state of the moisture in the plant. The ambiguity of some plant-physiology nomenclature becomes obvious, for example, when one notes the more or less synonymous use of "turgor deficit" by Curtis and Scofield [see 2 of "References" at end of paper], "suction force" by Ursprung and Blum [13], "water-absorptive power" by Thoday [11], "suction pressure" by Stiles [10], "suction tension" by Beck [1], "effective (net) osmotic pressure" by Shull [8], and "diffusion-pressure deficit" by Meyer [7].

This difference in language has no doubt developed because the two fields of study have progressed almost independently of each other. It is a source of difficulty when one attempts to study the use of soil-moisture by plants, since some of these terms used by the plant physiologist and soil scientist cannot be translated into simple physical terms which are suitable for analytical purposes and of which the dimensions are known. In such a study, one may conveniently consider the soil, the plant, and the air as a combined system. Fortunately, the language of thermodynamics has been well developed and tested and is admirably adaptable to such a system. It has not, however, been widely used in the past either by soil scientists or plant physiologists. In this connection, Stern [9] has made an excellent contribution, but he has not discussed in particular the use of soil-moisture by plants. Gradmann [5] has done so and has tried to correlate some of the terms referred to above with more basic thermodynamic functions.

Several mathematical functions in thermodynamics have been invented for dealing with various problems. These and their application to soil-moisture will be discussed elsewhere [4]. In the short space available here, I shall merely discuss briefly some of the characteristics of the function called specific free energy as it applies to the soil, the plant, and the air as a combined system.

Thermodynamic properties of free energy

Interrelation of basic thermodynamic functions--Specific free energy is defined by the equation

$$f = e + Pv - Ts = h - Ts \tag{1}$$

where e, v, h, and s represent specific internal energy, specific volume, specific-heat content, and specific entropy, respectively, where by definition we have

$$e = q - w \tag{2}$$

$$h = e + Pv \tag{3}$$

$$s = (q/T) \tag{4}$$

in which w denotes the mechanical work performed and q the heat-energy per gram absorbed by the working substance of the system. We call them specific quantities because they refer to one gram of the substance, which, in the present case, is moisture. When dealing with larger masses, the function must, of course, be integrated or summed up for the total mass included in the system.

One might reasonably ask why such functions as the heat-content h and the free energy f are defined in such an apparently arbitrary manner with so seemingly little preliminary justification. Such functions are, as a rule, arrived at by some investigator making a mathematical analysis of a particular problem. During such investigations, a certain combination of mathematical terms describing physical quantities sometimes appears frequently in the equations. For convenience the investigator may give a particular name to such a combination. The justification for introducing such terms is evident only when one becomes familiar enough with their characteristics to appreciate their convenience and power in the analyses of problems. The genesis of such a term or mathematical function might be illustrated by the common practice of introducing the term h for the combination (e + Pv) in expressing the specific heat of a gas at constant pressure c_p where

$$c_p = d(e + Pv)/dT = (dh/dT) \tag{5}$$

For future use, it should be noted that

$$h = \int_0^T c_p dT \tag{6}$$

Also for future use we here recall the following well-known expression, a combination of the First and Second Laws of thermodynamics. It is

$$ds = (de + Pdv)/T \tag{7}$$

Now, from equation (3), if the pressure is kept constant,

$$dh = de + Pdv \tag{8}$$

From these two it follows that

$$ds = (dh/T)$$

and with equation (6) this becomes

$$ds = c_p(dT/T)$$

or

$$s = \int_0^T c_p(dT/T) \tag{9}$$

To bring out the useful characteristics of the quantity called specific free energy, let us transform equation (1) into several differential forms, as follows: The total work dw performed by a system may, in general, be separated into two parts (1) the work of expansion Pdv against an external pressure P and (2) any other mechanical work dw_m including electrical work that the system might perform. In general, therefore, the total work dw may be represented by

$$dw = Pdv + dw_m \tag{10}$$

Differentiating the first of equations (1), we have

$$df = de + Pdv + vdP - Tds - sdT \tag{11}$$

According to the First Law of thermodynamics [equation (2)] we have

$$de = dq - dw \tag{12}$$

Now, in any reversible process (that is, in a balanced process that proceeds infinitely slowly) we have [equation (4)] dq = Tds, which in combination with equation (10) makes equation (12) become

$$de = Tds - Pdv - dw_m \tag{13}$$

Substituting (13) into (11), we have

$$df = -sdT + vdP - dw_m \tag{14}$$

For changes in a system taking place at constant temperature dT = 0, while equation (14) becomes

$$df = vdP - dw_m \tag{15}$$

If also the external pressure P remains constant during the change, we have

$$df = -dw_m \tag{16}$$

or

$$-df = dw_m \tag{17}$$

Equation (17) means that if we have a reversible change taking place in a system at a constant temperature and pressure, the work dw_m done by the system, which is exclusive of the work of expansion against a constant pressure P, equals the decrease of the free energy (-df) of the system during the change. Thus for finite changes in the system the decrease in the free energy ($-\Delta f$) is a measure of the maximum work Δw_m (including both electrical and mechanical work, but excluding the work of expansion against a constant pressure) performed by the system, at constant temperature and pressure on its surroundings.

We have just considered infinitesimal changes. Let us now consider finite isothermal changes in a system from a state A to a state B. Since dT = 0, we have therefore, from equation (15),

$$\Delta f = \int_A^B df = f_B - f_A = \int_A^B vdP - \int_A^B dw_m \tag{18}$$

From this the three following cases arise:

If the pressure remains constant throughout the isothermal change of state, dP = 0, while equation (18) becomes

$$\Delta f = f_B - f_A = -\int_A^B dw_m \tag{19}$$

where the negative sign before the integral makes the whole quantity represent work done on the system by the surroundings. Without the negative sign, the whole quantity would represent work done by the system on the surroundings. Equation (19) states that in finite isothermal, isobaric changes of state of a system from A to B, the increase in the free energy Δf of the system equals the work $(-\int_A^B dw_m)$ that must be performed on the system in carrying it from A to B. As already pointed out, this integral does not include any work of expansion against the constant pressure of the atmosphere, as when water is evaporated from the leaves of plants. In other words, the free energy Δf of a system in the State B with respect to a datum A equals the work that must be done on the system at constant temperature and pressure to bring it from the datum A to the State B. Another way of stating in words the facts presented in equation (19) is that the decrease in the free energy $-\Delta f$ of the system in going from State B to State A equals the total work done isobarically and isothermally by the system on the surroundings, excluding any work of expansion against a constant pressure.

If, on the other hand, no work is performed during the finite isothermal change--that is, if $\int_A^B dw_m = 0$ -- then equation (18) becomes

$$\Delta f = f_B - f_A = \int_A^B vdP \tag{20}$$

Thus the mere increase of the hydrostatic pressure P on the system will increase its free energy.

If, furthermore, a reversible process occurs at constant temperature and pressure, with no work being done by the system, except an expansion against a constant pressure, equation (13) or (20) becomes

$$\Delta f = f_B - f_A = 0 \tag{21}$$

Equation (21), as will be shown later, describes the conditions of a system at equilibrium or where two or more phases remain in equilibrium. Suppose, for example, the two phases, water and vapor, are in equilibrium at 100°C. Then equation (21) says that the free energy f_B in the vapor-state equals that in the liquid state f_A. If heat is added to the water so as to vaporize one gram of water at 100°C and at a pressure of one atmosphere, then no change in free energy will be experienced. This follows because the temperature and pressure remain unchanged and no work is done during the vaporization except the expansion against the constant pressure of the atmosphere.

An expression enabling one to determine the dependence of the absolute free energy of moisture, for example, on temperature will now be given. Knowing the absolute value of the entropy s as defined by equation (9) and the heat-content h as defined by equation (6), we can express the specific free energy f previously defined by

$$f = h - Ts \tag{22}$$

in another useful form. From equations (6) and (9), equation (22) becomes

$$f = \int_0^T c_p dT - T\int_0^T c_p(dT/T) \tag{23}$$

Hence if c_p is known as a function of temperature, all three of the thermodynamic functions s, h, and f may be computed as indicated above.

Relation between changes in free energy and work performed in reversible and irreversible processes--In all reversible processes of a system occurring at constant temperature and pressure, it has been shown from equation (17) that the maximum work dw_m obtainable from the system is equal to the decrease in its free energy. That is, for finite changes

$$-\Delta f = \Delta w_m \tag{24}$$

In practice, however, all processes are irreversible to a greater or lesser extent; otherwise they would have to occur so slowly that they would never be completed. If an isothermal process is to occur with a finite velocity, the process will be irreversible, and some of the mechanical work will be irretrievably lost in the form of heat, so that we always find

$$-\Delta f > dw_m \tag{25}$$

In other words, the mechanical work dw_m performed in a natural process or transformation is less than the decrease in free energy occurring in the process. The difference $(dw_m - dw_m')$

represents a loss in mechanical energy. It generally becomes heat-energy at a temperature too low to be available for work in the system under consideration.

Free-energy changes of natural processes--Any natural spontaneous process must be irreversible to a greater or less extent. This follows because not all the forces of the system can be completely balanced at all times. If they were, so as to satisfy the condition of reversibility, the process would go on infinitely slowly and would therefore never be completed in a finite time. In order that the process may be carried out in a finite time, there must be an inequality in magnitude of opposing forces. In other words, there must be a resultant driving force of the process. The greater the force, the greater the irreversibility of the process. In all such cases the decrease of the free energy $-\Delta f$ is greater than the useful work accomplished $\Delta w_m'$. That is,

$$-\Delta f > \Delta w_m' \tag{26}$$

We have considered above the change in the free energy $-\Delta f$ of the system when there has been interchange of useful work $\Delta w_m'$ with the surroundings. We shall now consider a case where $\Delta w_m' = 0$ -- that is, where no work is done on the surroundings -- in which case we have

$$-\Delta f = -(f_2 - f_1) > 0 \tag{27}$$

Assume a closed system in which spontaneous changes are taking place and where there is no interchange of work with the surroundings and, therefore, where $\Delta w_m' = 0$. This might correspond to a spontaneous change in a system such as one composed of a moist and a dry soil placed in contact. Let us suppose for convenience that we have enough of the wet and dry soil so that their total moisture is one gram. Moisture will spontaneously go from the moist to the dry soil, and the process will be irreversible. We shall let f_1 represent the average free energy of the moisture initially, and f_2 the average free energy in the soil after the spontaneous change has taken place. Since $\Delta w_m' = 0$, equation (26) shows that

$$-\Delta f = -(f_2 - f_1) > 0 \tag{28}$$

or

$$\Delta f = (f_2 - f_1) < 0 \tag{29}$$

That is

$$f_2 < f_1 \tag{30}$$

As moisture continues spontaneously to flow from the moist to the dry soil, the initial average free energy f_1, of the system, decreases to f_2.

We may thus conclude that when any spontaneous change occurs at constant temperature and external pressure, the free energy of the system will invariably decrease. That is, the free-energy change Δf is always negative; or, stated algebraically, we have for all spontaneous changes

$$\Delta f < 0 \tag{31}$$

Never in any spontaneous change will the free energy increase.

Condition of equilibrium--It was shown for an isothermal reversible process occurring at constant pressure that $-\Delta f = \Delta w_m$. If we are dealing with an isolated system that can perform no net work on the surroundings except an expansion against constant pressure, we must set $\Delta w_m = 0$; that is, $\Delta f = 0$. Now, at equilibrium, any possible infinitesimal displacement is also reversible; that is, all forces are completely balanced. The work done Δw in any possible infinitesimal displacement at equilibrium must, therefore, equal zero because there is no resultant force in any direction at equilibrium. Since for any infinitesimal process occurring at constant temperature and pressure while the system is at equilibrium we have $\Delta f = 0$, it follows that the state of equilibrium of a system may be defined by

$$\Delta f = 0 \tag{32}$$

Specific free energy of several phases of the same substance in equilibrium with each other--Often we have to deal with a system composed of several phases such as ice, water, and vapor in equilibrium with each other. Changes in the free energy of our system now may consist of changes in free energy per unit-mass in going from one phase to another one. If two phases are in equilibrium with each other, any infinitesimal change in the variables of state of the system will not change the total free energy of the system.

This means then that when a gram of ice melts or a gram of water freezes or vaporizes, no change in the total free energy of the system occurs as long as both the temperature and pressure remain constant.

The change in free energy of the system when one gram of water vaporizes under equilibrium-conditions is given according to equation (32) by $\Delta f = 0$. Here Δf represents the change in free energy of one gram of the substance when it changes state. That $\Delta f = 0$ is simply a statement of the fact that the free energy of the substance is the same in the two phases. As long as the two phases are present together, equilibrium will be maintained. For finite changes of the free energy of the system at equilibrium we therefore have

$$\Delta f = (f_2 - f_1) = 0$$

That is, if f_1 is the specific free energy of the substance (water) in the initial phase and if f_2 is the specific free energy of the substance (vapor) in the final phase we have $f_1 = f_2$. Thus, if two phases coexist at equilibrium, their specific free energies are the same.

Negative character of the free energy of water in unsaturated soils and in solution--As is shown by the discussion above, the specific free energy of a system or substance decreases in any spontaneous change. Let us consider a body of free water in contact with an unsaturated soil. In common experience, water flows spontaneously from free water (whose specific free energy we shall call f_1) into an unsaturated soil (whose specific free energy we shall call f_2). It is customary to use pure free water under a pressure of one atmosphere as the zero-point or datum for the free energy of soil-moisture. Thus the free energy under these conditions is assumed to be zero. We have shown in connection with equation (25), in going from an initial state f_1 to a final state f_2, that for any spontaneous change in the case where $\Delta w_m' = 0$, it follows that $\Delta f = (f_2 - f_1) < 0$ or $f_2 < f_1$. But since $f_1 = 0$, f_1 being the free energy of our datum, we have $f_2 < 0$. That is, the free energy f_2 of the unsaturated soil-moisture is negative. This inequality states the general fact that the free energy of soil-moisture in all unsaturated soils is negative with respect to our commonly accepted datum. Only where the soil-moisture is under a positive hydrostatic pressure greater than one atmosphere could the free energy of the soil-moisture become positive.

Let us go further and consider the relation of the magnitude and sign of the free energy of a wet soil with respect to that of a drier one. Since it is a common experimental fact that moisture will flow spontaneously from the wet to the dry soil and since we are here considering spontaneous changes, let us take the wetter soil as the initial state of the soil-moisture having the free energy f_1 and the drier soil as the final state of the soil-moisture having the free energy f_2. For spontaneous changes, we have $f_2 < f_1$, which states the general fact that the free energy f_2 of a dry soil is less than the free energy f_1 of a wet soil.

In common experience, likewise, if pure water is separated by a semi-permeable membrane from water in a solution, and if the pressure is the same on the pure water as it is on the solution, water will tend to move into the solution. The free energy of the water in solution is thus seen to be negative.

The space-rate of change of free energy--The free-energy function is useful in studying the movement of water in the combined system composed of the soil, plant, and air. From equation (17) we have $-df = dw_m$ or since $dw_m = F d\ell$, where F represents a force per unit-mass and $d\ell$ represents an element of distance, we may write

$$(df/d\ell) = -F \qquad (33)$$

Equation (33) states that the space-rate of change of free energy represents a force per unit-mass in the opposite direction. This is the force which causes water to move (in the soil or plant, for example) in a direction such as to decrease its free energy. The similarity in definition between this and potential as used in electricity, magnetism, and mechanics is clearly seen. The gradient of the free energy at any point in the soil or plant therefore gives the negative of the force acting on the water at that point.

When water exists in a force-field such as a gravitational field, an electrical field, or an adsorptive field, it has a definite free energy, due to its position in the field, and there is, furthermore, a change in free energy due to a change from point to point in the field. The force acting on the water, due to the field, is given by equation (33). If, for example, we consider the water existing in the plant growing in soil, it will have a higher free energy, due to the gravitational field, up in the plant than it will down in the roots or in the soil.

If, however, water is moving up the plant, the total specific free energy will be less up in the plant than it will be in the soil.

We must remember, as was pointed out earlier, that the foregoing applies to an isolated system. By injecting energy into the system, as, for example, in the use of an electric motor to drive a pump, we may, of course, force a fluid to flow from a point of low free energy to one of high. The application of such a device in the plant will be discussed later.

The total specific free energy is composed of several components.

Let us now turn to a direct application of the foregoing ideas. We are here interested in the value of the free-energy function as applied to water in the various parts of our system: Soil; plant; and air. The total free energy Δf at any point in the system is composed of several component free energies

$$\Delta f = \Delta f_P + \Delta f_O + \Delta f_F + \Delta f_\sigma \qquad (34)$$

where Δf_P represents the free energy that the water has because of the hydrostatic pressure it is under, Δf_O is that due to presence of dissolved material giving the solution an osmotic value, Δf_F is that possessed by the water in virtue of its presence in a force-field such as the gravitational field or an adsorptive field, and $\Delta f\sigma$ is that which exists if the water is in an interface having an interfacial surface-tension σ. If the moisture in the whole system is in equilibrium, the total free energy Δf is a constant throughout according to equation (32); the component free energies, however, will in general vary greatly from one point to the next, but always so that their sum remains constant.

To evaluate the free energy of the water at any point in our system we must consider the evaluation of each component. By an appropriate relation applied to equation (34), we arrive [4] at the expressions (35), (36), (37), (38), and (39), given here without proof, for the total as well as the component free energies.

$$\Delta f = RT \ln (p/p_0) \qquad (35)$$

where p_0 is the vapor-pressure of pure free water taken as the zero-point of reference, p is the vapor-pressure of the moisture, and R is the gas-constant.

$$\Delta f_P = v\,\Delta P \qquad (36)$$

where v is the specific volume of the water and ΔP is the hydrostatic pressure on the water at the point in question.

$$\Delta f_O = -v\Delta P_O \qquad (37)$$

where ΔP_O is the osmotic value in the water at the point in question.

$$\Delta f_F = -\int_A^B K \cos\theta \; d\ell \qquad (38)$$

where K is the magnitude of a vector representing the force at a point in the force-field making an angle θ with the direction of the element of the path of integration $d\ell$, A represents the zero-point of reference, and B represents the point at which Δf_F is to be evaluated.

$$\Delta f_\sigma = \sigma/\gamma\rho \qquad (39)$$

where σ denotes the surface-tension, γ is the thickness of the capillary layer, and ρ is the average density. To evaluate some of these components is sometimes impossible. A neglect, however, of their possible existence has been the cause of some confusion.

The relative value of each component of free energy changes enormously from point to point in the air-plant-soil-moisture system. There seem to be at least three possible techniques for studying and determining the value of the free energy throughout our system.

(1) Equation (35) permits us to get a value of the total specific free-energy change between any two points when the vapor-pressure can be measured. This would no doubt be difficult to do directly for different parts of the plant. A technique, however, might be developed for measuring the vapor-pressure at localized points of the plant.

(2) Cryoscopic methods may be used and, if they are, it must be recalled [equation (37)] that an increase in the osmotic value causes a decrease in the free energy, whereas an increase in the hydrostatic pressure [equation (36)] causes an increase in the free energy. On the other hand, either an increase in the hydrostatic pressure, if common to liquid and crystals [4] or an

increase in the osmotic value will depress the freezing point. If we are to use cryoscopic methods to evaluate the free energy, we must, therefore, distinguish between these two effects.

(3) Plasmolytic methods permit us to evaluate the free energy of the water in the plant at localized points. The free energy of the plasmolytic solution in equilibrium with the region equals, of course, the free energy of the water in that region of the plant. It does not follow, however, that the osmotic value of the solution in the plant is the same as that of the plasmolytic solution.

As equation (33) shows, the rate of change of the free-energy function with distance represents the negative of the force per unit-mass acting on the water. The importance of evaluating the free energy and its rate of change with respect to position in the plant in studies of water-movement, is accordingly emphasized.

Force causing water to move through plants

Consider a possible condition such as the following under which a tree might be transpiring water. Assume that the soil in which the tree is growing is dried out to the permanent wilting-percentage [14] and that the air surrounding the transpiring leaves of the tree has a relative humidity of 40 per cent at 30°C. The total free energy of the soil-moisture surrounding the roots at the permanent wilting-percentage calculated from the vapor-pressure measurements [3] is about -0.2×10^8 ergs per gram, whereas, according to equation (35), that of the air at 40 per cent relative humidity is -9.4×10^8 ergs per gram. This gives a total overall drop in free energy from the soil-moisture to the air of -9.2×10^8 ergs per gram. If this drop occurred through a tree ten meters high, there would, according to equation (33), be an average force tending to pull water up the tree of 9.2×10^5 dynes per gram--a force of approximately 1,000 times gravity. At points in the soil or plant where the rate of change of the free energy is greatest, the force is probably much greater than this. Those points in the soil-moisture-plant system that offer the greatest resistance to flow will show the greatest rate of drop of the free energy. The rate at which the water moves up the tree depends, of course, upon the resistance to flow of the different parts of the plant concerned with conduction.

Some measurements available permit us to estimate the drop in free energy in various parts of plants. Kramer [6], working with sunflower plants at 25°C, measured the rate of use of water while the roots of the plant were in free water. He then cut off the roots under water and continued to measure the rate of absorption of water through the plant. He found that the rate of use after the roots were cut off was about the same as before, indicating that the drop in free energy of the water while passing through the roots, under the conditions of the experiment, was not great as compared with the total drop in free energy experienced by the water in passing through the entire plant.

Thut [12] reports measurements of relative humidity of leaf-tissue and stomatal openings in a sunflower at temperatures near 22°C enabling one to calculate the free-energy drop from the leaf-tissue to the air. He reports the relative humidity of the leaf-tissue as being 99.4 per cent, and that in the stomatal opening as 94 per cent. The free energy of the water in the leaf-tissue and in the stomatal openings may be calculated from these measurements by means of equation (35). An application of this equation gives -0.843×10^8 ergs per gram as the drop in free energy from the leaf-tissue to the space within the stomatal openings. An application of the same equation again gives a drop of -8.388×10^8 ergs per gram from the space within the stomatal openings at 94 per cent relative humidity to the surrounding air at 40 per cent relative humidity. This gives a total drop in free energy between the leaf-tissues and the outside air, under the conditions of his experiment, of -9.231×10^8 ergs per gram; or, in round numbers, -9.2×10^8, the same as the figure given for the total drop in free energy in going from the soil to the air. This indicates that practically the entire drop in free energy occurs near the leaf-surface.

Unfortunately, however, we have no data available that have been collected specifically for the purpose of studying these free-energy drops through the various portions of the plant. The foregoing emphasizes, though, the need for measuring the free energy of the moisture in the different parts of the plant and the usefulness of the free-energy function in interpreting the flow of water from the soil into and through the plant.

Direction of motion of water in the phloem of the plant

Plant physiologists have debated, for many years, how carbohydrates are transported from the leaf to other parts of the plant. Some have accounted for the transportation of the material in the phloem and some through the xylem. In many discussions it is not clear whether the sugars are thought of as moving in solution with the water or by some other means. In this discussion, let us consider the motion of the water alone. The question is whether the water moves up or down in the phloem. If it moves down, it must obviously go from the phloem back into the xylem in some portion of the plant. How can this phenomenon be interpreted from the view-point of the free-energy concept that we have considered above? As was shown in equation (26), the free energy always tends to decrease in any natural process where external energy is not injected into the system. In other words, if water moves from the xylem to the phloem-tissue of the leaf in the absence of added energy, the free energy necessarily decreases. Thus under these conditions water could never go back into the xylem. If, however, the system receives energy from without, such a phenomenon is possible. If a "pump" exists and is supplied with energy by the Sun's radiation, water can be "pumped" from the xylem to the phloem-tissue of the leaf and then be forced by a pressure-gradient down through the phloem and back to the xylem. Under these conditions the hydrostatic pressure would be higher in the phloem-tissue of the leaf than in the phloem of the lower part of the plant. Such a "pump" would be formed by a system wherein a semi-permeable membrane separates the xylem and phloem-tissue of the leaf in which sugars are manufactured in the phloem-tissue of the leaf in the presence of radiant energy and are used up in the phloem-tissue lower down the stem, by the metabolic processes of the plant. This system is analogous to a water-pump in a pipe-line. This means that the free energy would be raised in passing through the "pump." The raising of the free energy can only occur while the "pump" is operating. The downward flow would continue after the light-supply was shut off as long as there was an adequate gradient in the concentration of the phloem. This is analogous to the condition where water is pumped into an elevated tank. The water will continue to flow from an outlet under the tank after the pump has stopped. The cooling of the upper parts of the phloem-tissue of the plant, however, would tend to slow down and may even reverse the direction of movement. Thus one might expect, under the fluctuating conditions of light-intensity, temperature, and relative humidity in which plants grow, to find the water moving down in the phloem at certain times while it might be moving up at other times.

Summary

(1) Attention is called to the desirability of using thermodynamics as a common language of soil scientists and plant physiologists in quantitative discussions on the use of soil-moisture by plants.

(2) Free energy is proposed as a useful thermodynamic function for this purpose; its properties are briefly discussed.

(3) Expressions are given for evaluating the various component free energies of water in the soil-plant-air system.

(4) The average force driving water through a plant under specified conditions is estimated.

(5) An estimate, from available data, is also made of the drop in free energy through certain parts of the plant.

(6) The flow of water in the xylem and phloem is discussed in the light of free-energy changes.

References

[1] William A. Beck, Osmotic pressure, osmotic value and suction tension, Plant Physiol., v. 3, pp. 413-440, 1928.
[2] O. F. Curtis and H. T. Scofield, A comparison of osmotic concentrations of supplying and receiving tissues and its bearing on the Münch hypothesis of the translocation mechanism, Amer. J. Bot., v. 20, pp. 502-512, 1933.
[3] N. E. Edlefsen, A new method of measuring the aqueous vapor pressure of soils, Soil Sci., v. 38, pp. 29-35, 1934.
[4] N. E. Edlefsen and Alfred B. C. Anderson, Thermodynamics of soil moisture (in press).
[5] Hans Gradmann, Untersuchunzen über die Wasserverhältnisse des Bodens als Grundlage des Pflanzenwachstums, I, Jahrb. Wiss. Bot., v. 69, pp. 1-100, Part I, 1928.
[6] Paul J. Kramer, Root resistance as a cause of the absorption lag, Amer. J. Bot., v. 25, pp. 110-113, 1938.
[7] B. S. Meyer, The water relations of plant cells, Bot. Rev., v. 4, pp. 531-547, 1938.
[8] Charles A. Shull, Absorption of water and the forces involved, J. Amer. Soc. Agron., v. 22, pp. 459-471, 1930.
[9] Kurt von Stern, Pflanzenthermodynamik, Berlin, 412 pp., 1933.

[10] Walter Stiles, The suction pressure of the plant cell: A note on nomenclature, Biochem. J., v. 16, pp. 727-728, 1922.
[11] D. Thoday, On turgescence and the absorption of water by the cells of plants, New Phytol., v. 17, pp. 108-113, 1918.
[12] Hiram F. Thut, The relative humidity gradient of stomatal transpiration, Amer. J. Bot., v. 26, pp. 315-319, 1939.
[13] A. Ursprung and G. Blum, Zur methode der Saugkraftmessung, Ber. Deutsch. Bot. Ges., v. 34, pp. 525-539, 1916.
[14] F. J. Veihmeyer and A. H. Hendrickson, Soil moisture at permanent wilting of plants, Plant Physiol., v. 3, pp. 355-357, 1928.

University of California,
Davis, California

DISCUSSION

WILLIAM A. BECK (University of Dayton)--(1) It is evidently desirable to give a commonly accepted and satisfactory quantitative expression to the motive power which causes water to be translocated from the soil, to the plant and finally to the atmosphere. It is furthermore desirable to give satisfactory expression to the relata involved.

(2) The problem of giving such expressions to the motive power for such translocation of water is clearly a problem of biophysics.

(3) The thermodynamic system proposed by Edlefsen is adequate and logically deduced.

(4) The expression of potential-differences in function of free energy is sound and should be helpful in determining the physical differences of soils and also in determining the bearing of such physical differences on the physiological activities of plants.

(5) The analogy of the pump which produces circulation in a pipe-line with the physiological activity of the plant is particularly apt.

(6) A satisfactory explanation of the essence of the motive power which causes the translocation of water from the soil to the plant and finally to the atmosphere must be a physiological one. This does not imply that the laws of thermodynamics do not hold in a biological system, but merely that we are not fully acquainted with all of the entities and realities involved in the operation. What is evident is that there is a motive power comparable to that of a pump which, however, is adaptable to the needs dictated by external factors. There is a considerable body of evidence on hand to prove that the osmotic value of cells and tissues and the suction tension and turgor and wall pressure of a plant are dependent on the resistance which the soil offers to the flow of water from the soil to the plant. The motive power increases with the resistance. This accounts, for example, for the greater sugar-content in the cane of the Everglades when the season is dry.

(7) Employing the data furnished by Ursprung [Proc. Internat. Cong. Plant Sci., v. 2, pp. 1081-1094, 1929], the thermodynamic expression of the relata as indicated by Edlefsen might be determined. These determinations might be very helpful to the plant physiologist in his effort to give a satisfactory physical explanation of the phenomena which are very unusual and physically apparently paradoxical--for example, the "endodermis pump" and "polar differentiation of the suction forces" in the absorption-zone of the root of Vicia Faba.

S. C. BROOKS (University of California)--The problem posed by the motion of water in the phloem merits more detailed analysis. In this we may use the following superscripts: LX for leaf xylem, in which f_O^{LX} and f_p^{LX} will be taken as equal to zero; LP for leaf phloem; and X and P for xylem and phloem in the lower plant. Other components of f will be disregarded and only isothermic processes will be considered.

Diffusion of carbohydrates into the leaf phloem (which surrounds the leaf xylem) lowers the free energy of the water so that a $\Delta f_O^{LP} < 0$ is set up. The free-energy gradient from the leaf xylem leads to movement of water through plasma membranes offering a considerable mechanical opposition to this movement, but nevertheless the entering water sets up a hydrostatic pressure in the phloem leading to a $\Delta f_p^{LP} > 0$; at equilibrium $\Delta f_O^{LP} = \Delta f_p^{LP}$, but since a mass-movement of sap down the phloem (where less mechanical opposition is assumed) prevents attainment of equilibrium, so that $(\Delta f_O^{LP} + \Delta f_p^{LP}) < 0$.

In this mass-movement both water and carbohydrates move down to the lower plant where a set of metabolic reactions leads to a diminution of the osmotic pressure. This is equivalent to an increase in free energy of the water of the sap, so that, referring Δf_O-values to Δf_O^{LX} in the leaf xylem, which is assumed to be equal to zero, $0 > \Delta f_O^{P} > \Delta f_O^{LP}$. This metabolism both stores reserves for later use and oxidatively removes the carbohydrate intake.

For water to pass from stem phloem to xylem this change must go on until f_O^{P} rises in value until it is equal to zero. This neglects gravity, so that $f_O^{X} = f_O^{LX}$ The crux of this situation lies in the different mechanical resistances offered by the structures present in the partition between xylem and phloem in the leaf, and that offered by the leaf and stem phloem.

Ursprung and Blum [1] describe an apparent difference in "suction force" of inner and outer walls of endoderm cells. Provided no errors of technique occur an analysis of this situation would be interesting. This must be done by separating the factors affecting the free energy of water, namely, those of hydrostatic pressure, osmotic forces, fields of force, and surface-tension.

Lack of specific knowledge of these factors in Ursprung and Blum's experiments seems to make it unprofitable for me to assay this analysis here. But it must be true that osmotic pressure and hydrostatic pressure factors, and possibly interfacial tension factors are important. It is difficult to visualize any directional effect of fields of force due to adsorption in this experiment.

Reference

[1] A. Ursprung and G. Blum, Eine Methode zur Messung polarer Saugkraftdifferenzen, Jahrb. Wiss. Bot., v. 65, pp. 1-27, 1925.

HAROLD H. CLUM (Hunter College)--Although I am most interested in this general field of the water-relations of plants, I have no new data at present which might be used for further calculations of the free energy of water in various parts of the plant.

Personally I am fascinated by this new approach to the subject. If more of us learned to use the language and equations of thermodynamics we ought to be able to avoid some of the rather wild speculations which have been made regarding the movement of water and solutes in plants, and we would be able to see more clearly the kind of data which are necessary to clear up some of the debated points.

One sentence of your paper troubled me. Possibly it is a misprint. It reads, "Such a 'pump' would be formed by a system wherein a semi-permeable membrane separates the xylem and phloem-tissue of the leaf in which sugars are manufactured in the phloem-tissue of the leaf in the presence of radiant energy and are used up in the phloem-tissue lower down the stem, by metabolic processes of the plant." Did you mean to imply that the sugars are manufactured in the phloem? Do we have evidence that they are manufactured there? Or may not the chlorophyll-containing parenchyma of the leaf make up part of the system or "pump"?

R. H. COTTON (The Pennsylvania State College)--(1) Entropy or s equals $\int_0^T c_p(dT/T)$ for a substance in crystalline form at temperature T compared with its entropy, as a crystal, of zero at T = 0. If the substance is melted or vaporized in the change of state under consideration the entropy will include the heat of fusion or vaporization, or both, as the case may be, divided by the temperature at which melting or vaporization occurs. Thus the absolute entropy of water at 110°C at one atmosphere, external pressure, is

$$\int_0^{270} [(c_p)\ \text{ice}/T]dT + (\text{heat of fusion})/273 + \int_{273}^{373} [(c_p)\ \text{water}/T]dT$$

$$+ (\text{heat of vaporization})/373 + \int_{373}^{383} [(c_p)\ \text{steam}/T]dT$$

Usually, however, since $-(\Delta F)$-change only is desired, there is no need for absolute entropy, but only changes in entropy. The same may be said of heat-content, H.

(2) In discussing the free energy of soil and the free energy of moisture in the soil, one should be careful not to use them interchangeably as they are different.

(3) If the basis for formula (35) is one gram then it should read $\Delta F = 1/M\ RT \ln (P/P_0)$ where M is the molecular weight of the compound under consideration.

(4) The usefulness of the concept of free energy is well shown by the author's example using Thut's data--that is, the property which determines how water will flow in a system is not its vapor-tension or osmotic pressure or root-pressure, but its free energy. Therefore, free energy is a fundamental concept by which to express data in the study of water-relations.

A. S. CRAFTS (University of California)--I have much sympathy for your effort to introduce a more exact terminology into the fields of plant physiology and soils. Your example illustrates well the confusion that results when various investigators coin a number of terms to describe identical relationships, and their use becomes general throughout the literature. In selecting the inter-related fields of soil and plant-water relations as a point for introducing this new terminology you have chosen well, for there is probably no other in which the language has become more confused.

In making the change to the thermodynamic terminology, two facts should be frankly recognized. First, few of the older men in plant physiology and soils will be able to read this new language without considerable study; whereas many of the younger ones can read it intelligently, few can make the necessary substitutions to be able to use the equations with ease. If it is to become the Esparanto of biological science, the curricula of our colleges will have to be changed to include practice work in thermodynamics among their required courses.

Second, for the biologist, thermodynamics is at best merely a tool, a means toward an end and not an end in itself. The exact statement of a biological relationship does not explain it; although a clear statement will aid in the visualization of the problem, the fundamental task of solving it in terms of a physical or chemical mechanism remains.

Now this consideration brings up the question as to the best method of adopting the thermodynamic terminology. Should we as scientists, using the methods becoming so popular today, attempt, by organized action, resolutions and polls, to take on this new language in one major operation? I am afraid this would not be successful.

On the other hand, as we push forward in the solution of our various problems to more exact knowledge, we naturally attempt more exact descriptions and mathematical solutions. The limiting factor here becomes our individual abilities to handle mathematics, and as our needs become apparent, they are gradually reflected in curricular changes. Is this more natural growth too slow?

We must all recognize that many, probably most, of our biological problems will not yet submit to exact mathematical analysis. The two cases that you have cited, namely the absorption and rise of water in plants, and the movement of water in the phloem may be used as examples. In the former, although we may have a fairly acceptable mechanism to explain the over-all functioning of the root in water-absorption [Crafts and Broyer, Kramer] studies of Hoagland and Broyer and Grossenbacher, to mention only a few, show how complex and unpredictable the functions of ion-absorption and root-pressure may be. Water-movement in the phloem is regulated not only by water-balance which affects rate, but by concentration-gradients that determine direction. Water-balance is the resultant of the above factors of water and ion-absorption as reflected in root-pressure and all of those affecting water-loss including stomatal opening. Concentrations in turn reflect the balance between synthesis utilization and storage of organic compounds, functions of complex nature.

Even in soils, which some continue to consider as masses of inert minerals moistened by water, modern chemical and microbiological studies have shown how rapidly and unpredictably changes may occur. And so, even with an exact and satisfactory language with which to analyze his results, the primary work of the biologist is to perform the critical experiment. And even though at times it becomes necessary, as you have done, to oversimplify the problems for analytical purposes, the duty of the biologist is to recognize and describe his phenomena in all of their baffling complexity. To return to your specific cases, regarding phloem-function, I think we can all agree with Mason and Phillis [1] when they say, "Until the physicist knows more concerning the nature of liquids ...... and the biologist knows more about the physics of protoplasm, it is impossible to say how the diffusion of solutes (or water) is accelerated in the sieve-tube."

And concerning the more general problem of soil-plant relations, we can agree with Hoagland [2] that "The discussion (of the plant as a metabolic unit in the soil-plant system) may be appropriately closed by emphasizing again the general view that problems of the soil-plant system cannot be solved without the aid of patient and laborious experimentation under conditions which permit the requisite control of the plant's environment and the quantitative measurement of processes or of their end products. Such researches are indispensable to the development of scientific knowledge in the field of geobotany or of practical agriculture."

I would like, in closing, to point out what to me seems to be a discrepancy in your calculations. You arrive at the conclusion that the force moving water from the soil through a tree ten meters high is equivalent to approximately 1,000 times gravity. Meyer and Anderson in their text [3] say, "Such a pull (one thousand times gravity) is equivalent to a pressure of about one atmosphere". Now Veihmeyer and Hendrickson showed that at permanent wilting, a force equivalent to 16 to 20 atmospheres was required to take moisture from the soil. According to Dixon's calculations, a force of at least two atmospheres would be required to carry it to the top of a tree ten meters high. This indicates that a force equivalent to 18 to 22 atmospheres would be required whereas your calculation indicates a force equivalent to only one atmosphere. Can you clear up this point for me?

References

[1] T. G. Mason and E. Phillis, Some comments on the mechanism of phloem transport, Plant Physiol., v. 16, pp. 399-404, 1941.

[2] D. R. Hoagland, The plant as a metabolic unit in the soil-plant system, reprinted from Essays in Geobotany in Honor of William Albert Setchell, pp. 219-245, 1936.

[3] B. S. Meyer and D. B. Anderson, Plant Physiol., D. Van Nostrand Company, New York, 1939, 696 pp.

H. C. EYSTER (University of South Dakota)--There is a diversity of opinions among botanists, among plant physiologists, among physicists and physical chemists, and among the members of all three groups concerning the definitions of osmosis and osmotic pressure. A partly completed study by me shows that there are four common concepts of osmosis. They are (1) osmosis is the diffusion of a solvent (water) through a membrane, (2) osmosis is the diffusion of a liquid through a membrane, (3) osmosis is the diffusion through a membrane, and (4) osmosis is the diffusion of a substance through a membrane. Some of these are synonymous from certain points of view. For example, the first concept is the same as the second provided that liquid means solvent and not solution.

Concept	General botanists	Plant physiologists	Physical chemists
First	5	5	7
Second	5	2	0
Third	5	2	0
Fourth	6	2	3

Likewise, different concepts of the term osmotic pressure exist. These concepts are (1) osmotic pressure is the diffusion pressure of the solute molecules, (2) osmotic pressure is hydrostatic pressure of turgor pressure, (3) osmotic pressure is the maximum hydrostatic pressure developed, (4) osmotic pressure is theoretical mechanical pressure exactly equal and opposite to the tendency of solvent to diffuse into a solution of the same solvent, (5) osmotic pressure is the pull that the cell-sap is capable of exerting upon pure water if it were separated from it by a perfectly semi-permeable membrane, and (6) osmotic pressure is the diffusion pressure of water-molecules passing through a membrane. A very preliminary statistical analysis reveals the following:

Concept	Physical chemists	Concept	Physical chemists
First	2	Fourth	2
Second	4	Fifth*	0
Third	1	Sixth	1

*Is used by some botanists; the concepts of botanists on osmotic pressure have not yet been statistically analyzed.

Water need not move down through the phloem in order to have solutes move down. Solutes move independently under the influence of their own free energy and the movement is hastened by cytoplasmic streaming in sieve tubes of the phloem.

Sugars are not manufactured in phloem-tissue of the leaf. Sugars are formed in spongy chlorenchyma and palisade chlorenchyma tissues and transferred by diffusion to phloem for conduction to living cells where it is used immediately for growth and respiration and for conduction to permanent storage-tissues in stems, roots, fruits, and seeds.

While some sugars are used by living cells in phloem-tissue, most of it is stored in parenchymatous tissues and used metabolically by all living cells, not merely by phloem-cells.

This paper is a very worthy and valuable treatise on the movement of moisture from soil into plants and then on into the atmosphere. It is believed that an understanding of the fundamentals in this subject will be promulgated by the paper. However, it will not be sufficient to untangle and undo all of the diversity of opinions. Our several groups need a standardization of useful terms. It is not enough merely to speak of free energy and its dissipation. The botanists and physiologists desire to have simple, exact terms to describe the movement of water into cells and from cell to cell.

W. GARDNER (Utah State Agricultural College)--The last term in your equation (34) gives me a little trouble. In the first place it seems to me that its dimensions are different from the other terms. Furthermore, would not f_0 vanish everywhere except at the surface? It would seem to me that the resultant field in the interior of the liquid would be the vector-sum of the gradients of the first three terms.

It seems to me that the engineers have used the term "pressure-energy" somewhat erroneously and somewhat the same misconception is conveyed in the term "free energy". I am sure you do not mean to imply in your statement "the mere increase of the hydrostatic pressure P on the system will increase its free energy", that increasing the pressure involves a transfer of energy, but I am wondering if many readers would not think so. I was pleased to note Epstein's comment [1] regarding the use of the term "thermodynamic potential". I believe it is preferable.

Reference

[1] P. S. Epstein, Textbook of thermodynamics, John Wiley and Sons, New York, p. 88.

G. A. GREATHOUSE (United States Department of Agriculture, Bureau of Plant Industry)--The proposed application of thermodynamics to the use of soil-moisture by plants by Dr. Edlefsen is to be commended. The plant physiologist should recognize more and more the importance of the applications of physics and chemistry to fundamental plant-problems, realizing that a mastery of these along with mathematics will aid in the understanding of his complex plant-soil problems. It is also timely to stop and consider the fallibility of such nomenclature as root-pressure, transpiration-pull, suction force, etc., used to explain the plant-soil phenomena.

Dr. Edlefsen recognizes the fact that it is difficult to evaluate some of the interrelated factors or components of the plant or soil in terms of specific free energy. Nevertheless by attempting to reason out our problems in these terms we learn of new existing components which have been responsible in part for the slow fundamental development within our applied sciences. It might be emphasized that the various thermodynamic properties such as free energy, heat-content, and entropy are no more than mathematical functions which can be calculated from measurable quantities such as heats of reaction, equilibrium-constants, and specific heats. The attempt of some to define heat-content, free energy, and entropy in a descriptive manner have often led to the mistaken impression that these quantities are associated with restricted physical processes. The thermodynamic functions can sometimes be very loosely interpreted in terms of physical processes, but their definitions are actually independent of such processes.

Other applications of thermodynamics to plant problems might be mentioned that are suggested by Dr. Edlefsen's paper, however, not directly considered. Valuable information on the swelling of plant-colloids (cellulosic materials, proteins, etc.) can be obtained without regard to structure or swelling mechanism by means of thermodynamic considerations. With the aid of the equation $P_s = -(RT/Mv_0) \ln (p/p_0)$ (where P_s represents the pressure that will just prevent further swelling and (p/p_0) is the relative vapor-pressure of the swelling medium in the p_0 swelling material, M is its molecular weight, v_0 is its specific volume, R is the gas-constant, and T is the absolute temperature), and moisture-content and relative-vapor-pressure data, the swelling pressures for any moisture-content can be calculated. (Space will not permit a discussion of some of the limitations of this equation.)

It is also possible to calculate the free energy of swelling from vapor-pressure data by means of the equation $\Delta F = -(RT/M) \ln (p/p_0)$ (where ΔF is the change in free energy occurring when a large amount of a partially swollen substance within which the vapor-pressure of the swelling medium is p takes up one further gram of the medium and R, T, M, (p/p_0) have the same significance as in previous equation). Likewise considerable insight into the mechanism of swelling can be gained from a comparison of the change of free energy ΔF with the differential heat of swelling ΔH. The difference between these two quantities is thermodynamically equal to the change in entropy ΔS times the absolute temperature, $\Delta S = (\Delta H - \Delta F)/T$.

Recently Dr. Rigler and I, in our experiments on quantitative comparison of methods for sterilizing solutions of organic compounds used in culture-media, noted a parallelism between steam-distillation of certain compounds and free energy of hydration. As an explanation for reduced volatility of water-soluble compounds, the property that water has of hydrating substances that it dissolves was considered. From this standpoint, compounds with polar groups are more soluble and less volatile than those without groups that can be hydrated. It was found that as the relative proportions of these groups per molecule decreases, volatility increases. For example, in Czapek's solution these losses were found: Benzoic acid 22.3 per cent; m-toluic acid 32.6 per cent; phenol 15.1 per cent; m-cresol 20.5 per cent; thymol 65.2 per cent, respectively. By the use of the equation $RT \ln (p/N)$, where p equals the partial pressure of solute over a dilute aqueous solution of molar fraction N, it was possible to calculate the free energy of hydration of various organic compounds that distill in steam. Whether the parallelism between steam-distillation of certain compounds and free energy of hydration is real or coincidental, the values secured show that the free energy of hydration and the steam-distillation constant change in a similar direction. Thus thermodynamic considerations of solutions to be used in culture-media are indicated to be of practical value. Also, these data indicate that esters would be far more volatile in steam than the corresponding acids or amines. Consequently the conversion of an acid to its ester might prove a suitable means of rendering it volatile in steam in cases where purification by other methods was difficult. This last statement is made to merely show that by thermodynamic calculations new applications may appear to the research worker.

R. E. HORTON (Consulting hydraulic engineer)--I believe you have done a valuable service in presenting the problem of utilization of soil-moisture by vegetation from the combined dynamic and thermodynamic viewpoint. Just how much practical value may come out of this line of approach remains to be seen, although I agree with you that it is important in order that factors involved in the study of these problems shall not be neglected.

Ultimately it seems to me that the force causing water to move through plants is solar energy and that the report might be carried one step further by an attempt to balance the available input of solar energy with the work performed in transport of sap.

Indirectly your report emphasizes something that I have felt for some time, and that is that we are much better informed regarding the phenomena of circulation of fluids in animal- than in plant-organisms.

I am rather surprised at the conclusion you apparently reach that most of the resistance occurs near the leaf-surface. From the hydraulic view-point and in view of the results of such meagre experiments as have been made on the flow of water through plant-tissues, and in view of the probably discontinuous passages through which water flows in a plant from the roots to the leaves, it would seem to me offhand that there must be a larger portion of resistance encountered between the roots and leaves than the calculations seem to indicate.

I note that you state that there is "an average force tending to pull water up the tree approximately 1,000 times gravity." I have often wondered if this really is "pull." I have followed Dixon's tension-theory of the ascent of sap rather closely from its inception and, while undoubtedly high tension can be produced in a continuous capillary column of pure fluid under suitable conditions, it has always seemed to me that the experimental determinations of tension in such water-columns fall far short of a complete analog of the phenomena taking place in the ascent of sap.

M. R. HUBERTY (University of California)--Professor Edlefsen's suggestion to substitute the term "specific free energy" for the many confusing terms used by plant physiologists and soil scientists to express the state of moisture in the plant seems a desirable one.

In equation (37) ΔP_0 is given as the osmotic value. It would probably be better to say osmotic concentration rather than osmotic value.

It is too bad that more data on the energy-losses through plants are not available. The straight portion of the curve obtained by Thut was drawn from three observations. Slight modification in these values would influence greatly the respective values obtained for relative humidity in the leaf-tissue and in the stomatal openings. However, this is not a criticism of the usefulness of the free-energy function but rather that the data supporting the contention that the drop in free energy within the plant proper is of second order of magnitude.

A. R. JORDAN (Montana State College)--The author of this paper is to be congratulated for pointing out the confusion of terms employed by writers in this work. By the adoption of a concise accurate terminology which is based on sound physical principles one may expect this field to advance most rapidly. The approach through a study of free energy or "Gibbs free energy" promises to be a very fruitful one. It might be emphasized that there is an advantage in using h in this discussion of a thermodynamic problem involving constant pressure since for such a case the change in h equals the heat absorbed. In view of the difficulty of performing direct measurements in this type of work, it is of special value to have a clear statement of the thermodynamic relationships which may be used in indirect measurements.

P. J. KRAMER (Duke University)--There is little doubt that simplification of the terminology used in discussing plant and soil-moisture relations would make for better understanding among those interested in this field. Theoretically, discussions of moisture relations might well be reduced to the terminology of thermodynamics, and expressed in terms of specific free energy. This would give a common terminology, useful in analyzing a variety of problems. Practically, however, it is doubtful if we should attempt to use this terminology in papers which are of general interest to workers in plant-science. The literature of plant and soil-moisture relations is not only of interest to soils men, plant physiologists, and ecologists, but also to workers in forestry, horticulture, agronomy, and other phases of applied botany. Most investigators in these fields are unfamiliar with the mathematics used in dealing with problems in thermodynamics and would be more puzzled than enlightened by an attempt to use the concept of free energy, expressed as ergs per gram of water, to explain water-movement. Everyone interested in water-relations, however, has some conception of the role of vapor-pressure or diffusion-pressure gradients in determining the direction of movement of water. They understand that water diffuses out of leaves because the vapor-pressure in the intercellular spaces is higher than that of the outside air, resulting in a diffusion-pressure gradient. It is also generally understood that a high vapor-pressure is associated with a high energy-level and a low vapor-pressure with a low energy-level. It seems, therefore, that for most physiological and ecological problems very little is gained by converting the vapor-pressure gradient into a gradient of free energy, expressed as ergs per gram of water. This view of course does not reflect on the value of the method for the mathematical analysis of special problems or in papers intended for specialists in certain fields.

M. R. LEWIS (Oregon State College)--I agree with you that there is need for better correlation of the work of plant physiologists and of soil physicists. It seems probable that the use of the known laws of thermodynamics by both groups is the most promising method.

For some time I have felt that another thermodynamic approach to study of the use of water by plants might be by an attempt to evaluate the different means by which the solar energy reaching a unit-area of a cultivated field is dissipated. The fact that the loss of water from isolated tanks of tules or other plants is much greater than from similar tanks set in the midst of large areas of the same type of vegetation might be explained in this way. The effect of heat-transfers by air-movements would complicate the problem but could probably be accounted for in some cases and neglected in others.

B. E. LIVINGSTON (Riderwood, Maryland)--It seems to me that this is an excellent presentation of the general thermodynamic background for considerations concerning movement of water from the peripheries of absorbing roots through the plant and into the air adjacent to the foliar surfaces. It should be an advantage to have these principles thus clearly stated in elementary style, since most students of plant-water relations are not adept at the application of thermodynamics and this line of approach may be helpful if more generally understood and appreciated. The book by yourself and Dr. Anderson will surely be even more valuable when it appears.

I think it is somewhat unfortunate that you seem to take up this presentation because of differences in terminology among various writers. That does not look like a good reason, does it? Terminology is always slow in crystallizing, but the material and energy-changes involved in the performance of soil, plant, and ambient air are real and require consideration, whatever they may be called. Your presentation forms a basis for considering them and it is thus just another and broader attack, with still other terminology. So far as you go in this paper, it does not appear that we are yet ready to discard the static concepts of soil-physics and physiology, which, as you do admit, have no doubt been useful. To me it seems clear that they will go on being useful, even after their thermodynamic basis may have become much more generally appreciated. Most students of plant-water relations seem to be hardly ready to consider the problem in terms of simple dynamics rather than in terms of static states such as pressures and the like. Most writers make their meanings fairly clear, I think.

While thermodynamics might be actually applied in a very simple case--for example, in considering water-loss by evaporation from a free liquid surface--its application in any case where soil and plant are involved is something to dream about; it is still pretty academic. The soil is complex enough to be troublesome, as you know, but the plant introduces a large number of special conditions. Its resistance to water-absorption and water-movement varies from hour to hour and from day to day. It is part of the province of physiology to deal with those resistances and their controls, and their consideration involves many additional concepts besides the basic principles of thermodynamics. I am reminded that meteorology seems to have solved most of the thermodynamic problems of precipitation, and yet each particular shower presents many difficult problems; I may understand pretty well how thunder-storms are produced and just what sorts of energy-changes are involved, but I shall have to be cagey in trying to reply if you ask why any particular shower behaves just as it does.

Every now and then some student brings up the question of special energy-release within the living tissues, due to metabolism. "Root-pressure" is known to exist, secretion pressures of various sorts, as in glands, etc. For example, why does water flow outward through an active nectary or guttating hydathode, when most of the water-movement is from root-periphery to leaf-periphery? I do not think anybody knows, but it does look as though energy of respiration (which also produces water in the plant, by the way!) were accountable.

It would indeed by very nice if we had methods, and workers to use them, for measuring the thermodynamic state of a particle of water at any locus in its path from root-periphery to foliar air or to the ambient air. I agree with you that that cannot be done, even if some students would like to try to do it. It occurs to me that you might examine some of the simpler controls more in detail, for example, the absorption of solar energy and air-heat by the plant, the influence of air-currents flowing over the leaf, etc.

As I have said, I think this paper of yours is a definite contribution toward the understanding of an ideal case, but our plant is more like a partly worn-out automobile than it is like a Carnot engine! We have many such idealistic statements in physiology, as elsewhere--as when one says all life is a phenomenon of aqueous solution, most life depends on photosynthesis of complex carbon compounds from carbon dioxide and water. These statements are surely true, but they do not help us much in our attempt to understand plant-performance, do they?

Your theory about downward movement of water from leaves to roots may be helpful in the realm of theory. It has been suggested that perhaps water moves upward and downward at the same time in different parts of the vascular system. So far as we have gone, however, it seems highly improbable that there is any large amount of downward movement of water in an ordinary plant under ordinary conditions of growth. Downward movement of carbohydrate and oxygen seem to me not to be due to any downward streaming of solution. The pressure-gradient that is common in most plants most of the time must be transmitted in all directions, through all tissues and its effect should be to move water from roots to leaves; the flow is, of course, most rapid in the paths where resistance to liquid movement is least. I see no reason, however, why we should not think of water moving upward in the phloem as well as in the xylem, albeit very slowly in the phloem. It seems likely that water might be moving upward and sugar downward in the same phloem-element.

The paper appeals to me as presenting an interesting fundamental aspect of plant-water relations, although it seems to me unlikely that these ideas may be applied to avoid discussing the detailed mechanisms by means of which plants are what they are.

W. F. LOEHWING (The State University of Iowa)--I wish to say that this project appeals immensely to me. It is obvious that the material has been thoroughly considered. Your report is an excellent formulation of the fundamentals which deserve recognition by plant biologists. I myself would like to see a report of the sort which you have presented published in a journal widely read by plant scientists in order that this view-point may be called particularly to their attention.

W. E. LOOMIS (Iowa State College)--For the purposes of your report, of course, the material as it stands is desirable, but you might keep in mind that many of the people you would like to reach cannot readily understand the paper in its present form. Second, we have been using in our own teaching and writing [1], the term "activity" in what we have intended to be synonymous with your term "free energy." I see no objection at all to changing to free energy, but I wish that we had a single word, and particularly a single word which would indicate the decreases or negative free-energy values with which we are particularly concerned, and it is this situation which has given rise to such unwieldy things as diffusion-pressure deficit. Two other points may be pertinent in this discussion. Your calculations give the free-energy drop for Thut's work on leaves, a value equal to the difference between the soil at the wilting-percentage and the air surrounding the tree. I have suspected an error in Thut's calculations, and I think that your analysis here indicates this very clearly. Thut had no such free-energy drop since his leaves were standing either in water or in plants growing in adequate soil-moisture supply. Stomatal closure or some other factor may be the explanation here. We are faced also with an unexplained break at the wilting-percentage of soil. The wilting-percentage of the soil represents a certain level of free energy as you have stated, but the free-energy level of the water of the plant, as Veihmeyer and Hendrickson have shown, has little or no effect on this semi-equilibrium point between plants and soil. The type of plant or the free-energy gradient does not appear to be a factor. We have been wondering if the phenomena is not related to the separating cellulose membrane which is uniform for all plant-materials, and it is essential only then that the free-energy level of the plant-water be below that of soil at the wilting-percentage. When this energy-level is reached, some breakdown in the membrane inhibits or sharply reduces further transfer of water as the liquid. Our figures suggest that a slow transfer, either of a decidedly different order of liquid, or a transfer of vapor continues for a considerable period. Final end-points depend more upon the continued life of the plant than upon characteristics of the soil-moisture-energy curves.

Reference

[1] W. E. Loomis and C. A. Shull, Experiments in Plant Physiology, McGraw-Hill Book Company, p. 67, 1939.

E. C. MILLER (Kansas State College)--To begin, we all agree that it would be a fine thing if we had a more nearly uniform terminology for many of the facts relative to soil and the plant. The objection to the method now is that it would take too much training for an individual to master the science of thermodynamics, in addition to his training as a soils man or as a plant physiologist. That seems to be by far the main objection to the proposition at the present time.

I frequently wonder what is our destination as scientists, because we are becoming so specialized in every phase of our work that it takes years to master a single narrow field. Whether we will be able, ourselves, to change the course of events or whether we must await some catastrophe to cause us to change our present set-up in scientific procedure, I do not know. But I do know that at the present time, it seems almost impossible for one to become familiar with any more than just a single small region of scientific procedure.

O. W. MONSON (Montana State College)--In his discussion of the function called "specific free energy," the author has clearly shown the wide application of the sciences of physics, chemistry, and botany to such practical problems as the artificial application of water to growing plants, a practice largely responsible for the development and growth of the West, namely, irrigation. The sections, (1) Negative character of water in unsaturated soils and in solution, (2) Space-rate of change of free energy, and (3) The total specific free energy is composed of several components, particularly, can be applied to problems connected with irrigation and its companion, drainage.

The negative character of water in unsaturated soils, considered in the light of the specific free-energy function, would seem to apply particularly to drainage-problems, but also to such problems of irrigation as sub-irrigation, spacing of furrows, flooding, erosion, etc.

The space rate of change aspect suggests an approach to such problems as frequency of irrigation, amount to be applied at a time, and perhaps even method of application, such as sprinkling--which creates a more humid condition for the plant to grow in--versus application directly to the soil, as by flooding.

The analysis of the several components of total free energy can also be applied to a problem of irrigation, namely, the method of application of water to crops. As previously mentioned, the application by sprinkling creates a humid atmosphere for the plant to grow in. How does this affect the dissipation of energy by the plant in the absorption of moisture and the building of

The answer to this and many other questions pertaining to the use of moisture by plants will be found more quickly if, as suggested by Dr. Edlefsen, plant physiologists, soil physicists, and --I should like to add--irrigation-engineers, will more freely coordinate their efforts, one line of which should be directed toward the adoption of a standard terminology.

G. W. MUSGRAVE (United States Department of Agriculture, Soil Conservation Service)--Theoretical treatment of the possible relationships existing between certain variables undoubtedly has its advantages. One needs to bear in mind, however, that any equation is precise only insofar as the variables entering the expressed relations are completely and precisely represented. In the plant- and animal-world the complex of variables and their relationships can rarely be given precise quantitative expression. For example, the effect of light upon a living organism is inclusive of more than simple thermal energy. Where both animate and inanimate materials are included the difficulties are even more involved and seem to go beyond matters susceptible of treatment by thermodynamic procedures. Many years ago De Varigny stated "all living organisms generate heat . . . . according to their activity and their structure, but all produce it. In the same manner all organisms submit to the influence of the surrounding atmosphere, although all do not follow the variations."

The energy-relations of a soil-air-plant system are inclusive not only of those of the plants living upon the soil, but of the micro flora and fauna living within it as well. The effects of light, the evolution of heat and of gases--to mention but a few of the complexities--become a part of the problem.

For these reasons, experimental verification of theoretical considerations are of the utmost importance.

The treatment of the subject of soil moisture from the view-point of energy-relationships doubtless is fully acceptable to most workers. Neither is the importance of temperature as one of the factors questioned. But is a thermodynamic concept sufficient to encompass the problem of water-movement in both soil and plant or in a "soil-air-plant moisture system?"

M. L. NICHOLS (United States Department of Agriculture, Soil Conservation Service)--We are very much interested in this, and I personally feel that the thermodynamic approach to the problems involving soil-moisture and the plant-physiological reactions offers a real basis for understanding. From the standpoint of soil- and water-conservation, the desirability of a more basic understanding of these phenomena is of the greatest importance and the effectiveness of any practical methods depends upon them.

G. J. PEIRCE (Stanford University)--A discussion of the energies available, if they can be applied, for water-intake and water-lift always interests me. To say that "work is done" by the roots, root-hairs, or whatever else, as one of my former colleagues said, is meaningless as well as obvious; and to show, as Dixon and others have, that oxidative metabolism releases energy enough to lift all the water needed to even greater heights, does not do much good either because no one knows how this energy can be and is applied. I still find myself, like many another and better man, stumped, and welcoming any contribution to the subject.

HILDA F. ROSENE (University of Texas)--I have read your paper carefully and think that it is an excellent and timely approach toward systemization of our thinking; perhaps some day all plant physiologists will start with a background in physical chemistry to build upon.

Since I am accustomed to a notation using capital letters, I found it necessary to adjust to your notation using small letters and F to designate force instead of free energy. Is this a new trend in the literature of physical chemists?

It seems to me important to emphasize the fact that "living systems" by their very nature are not in thermodynamic equilibrium with the environment. This limits the application of classical thermodynamics to living systems but should not stop us from an attempt to systemize our knowledge in quantitative terms.

You state, in your paper, "the rate at which water moves up the tree depends, of course, upon the resistance to flow of the different parts of the plant concerned with conduction." Perhaps it would be better to add "as well as the force or forces which operate to transfer the water from one point to another in space." Your statement seems to imply that the rate of movement depends only upon the resistance.

In relation to Kramer's experiments you state, "he then cut off the roots under water and continued to measure the rate of absorption of the plant." This statement and also Kramer's paper raises a question in my mind as to the validity of such a statement. The plant includes both shoot and roots; strictly speaking Kramer's measurements furnished data which permit a comparison of the rate of water-intake by the plant with the rate of intake by the shoot. In the absence of roots is it possible to measure the rate of absorption through the sunflower plant? Some of us have compared the rate of water absorption by roots in the (a) presence and (b) absence of the shoot; it is interesting to note that in this case the roots, in the absence of the shoot, have not been considered the plant with the shoot cut off, although this is as logical as designating the shoot, in the absence of the roots, as the plant.

You may be interested in some recent work done in this Laboratory. It was found that sucrose or potassium-nitrate solutions with osmotic pressures of 5.14 and 2.0 atmospheres, respectively, stopped absorption in one or more local regions in the majority of attached and isolated onion roots at 25°C and 100 per cent relative humidity. If solute absorption did not occur when water-inflow ceased under these conditions, one might consider the critical pressure which stopped inflow a measure of the total free energy operating to bring about water-transport. Solute absorption, however, was not measured.

As you state in your paper, the opposing force in this case furnishes no information concerning the possible component free energies--electroendosmotic, osmotic, imbibitional, etc.--which may be present. But the difference of three atmospheres (in the presence and absence of the shoot) needs to be accounted for. In the present stage of the work we are not justified in assuming that this difference is due to a "pull" by the shoot.

It was found that when the leaves but not the roots were exposed to constant light and air at 50 per cent relative humidity and 25°C, absorption by local root-regions ceased when the osmotic pressure of the external solution was 6.5 atmospheres. In this case the difference may be attributed to transpiration-effects; change in free energy occurred but these data alone do not specify the position or the nature of the mechanism which is inhibited by the opposing force.

Does the fact that there was no pronounced difference between the osmotic pressures of solutions which stopped apical and basal-water entry indicate that the free energies of water in these regions under the given conditions are similar, and that, therefore, there is no gradient of free energies of water along the longitudinal axis, but there is a gradient of "resistances" in the sense of ohmic resistance--that is, frictional resistance to flow--since the velocity of basal inflow in roots of this age is in most cases greater than that of apical inflow?

The paper which deals with these measurements will appear in the May (1941) issue of the American Journal of Botany.

H. L. SHANTZ (United States Department of Agriculture, Forest Service)--I am, as you know, pretty well out of this field, and doubt if I can make any pertinent suggestions. One or two of the practical difficulties impress me. Often the greater the dynamic force the less the result, just as in evaporation-measurements on a practical basis, generally the greater the loss of water from a water-surface the less the loss from the surrounding land-area because the water is simply not there to be lost. Soil is hardly a homogeneous substance or even a permanent substance and changes continually. The plant is also a constantly changing system. In the plant-soil contact I have always felt that for some reason the limit of movement of water was controlled largely by the soil and that the increase or decrease in gradient to the tissue had little practical effect on the residual soil-moisture.

B. T. SHAW (The Ohio State University)--When soil scientists and plant physiologists jointly attack the "air-plant-soil-moisture system," there will be some hope of elevating our endeavors above the realm of empirical experimentation. Cooperative activity is only possible when there is a complete understanding between the cooperators. A common language, or at least languages that can be translated into like terms, is a prerequisite of understanding. The thermodynamic function proposed in the paper offers distinct advantages.

F. J. VEIHMEYER (University of California)--There will be some antagonism on the part of some of us who are interested in plant-physiology and who have been using the terms described in the first part of the paper, and who have definite ideas on how water moves through plants. It should be clearly understood, however, that the paper does not suggest the mechanism which causes movement of water into and through the plant. The point is made that if movement takes place, there must be a driving force, and since $(df/d\ell) = -F$, the measurement of the change in the free energy of the water in different parts of the soil-water-plant system furnishes a means of determining the direction of flow, and if the conditions are specified, the magnitude of the flow may also be calculated. The equation which gives the relation of free energy to the vapor-pressure differences, probably is the most useful.

The mathematical reasoning in the paper is the standard thermodynamical treatment and may be found in a number of textbooks. The paper serves as a means to acquaint soil- and plant-investigators with the usefulness of the method of reasoning and illustrates briefly how it may be applied to the soil-moisture-plant relations. Many of us read equations and follow the manipulations, but fail to realize their full significance. The paper helps to bring the meaning of the equations to the attention of investigators in the field.

Failure to think in terms of precise quantities has, as intimated in the paper, lead to ambiguity. One of these mistakes is illustrated by the assumption that the amount of water held in the soil in a funnel under a pressure-difference of about one atmosphere should give a result which is the same as that obtained by centrifuging the sample at 1,000 times gravity. The belief, in many cases, is because of the fact that one atmosphere pressure is 1,000,000 dynes per square centimeter (M/T^2L) and 1,000 times gravity is 1,000,000 dynes per gram (L/T^2).

I do want to put in a defense for a term which was suggested by Dr. Hendrickson and me several years ago, the permanent wilting-percentage. There is sufficient evidence to show that this is the amount of water held by the soil so tightly that about 16×10^6 ergs per gram are required to remove it, and that this moisture, while representing a narrow range of soil-moisture within which wilting occurs, can be determined within about one per cent of soil-moisture. It certainly is more convenient to use the term permanent wilting-percentage than the more exact statement "moisture held by the soil such that 16×10^6 ergs per gram are required to move it." Perhaps similar considerations may justify the use of some of the other terms mentioned in the paper.

F. W. WENT (California Institute of Technology)--Right at the beginning I should like to state that this discussion has interested me very much and that I think that from didactic considerations it is highly worthwhile. It gives a very clear analysis of the forces involved in water-movement and elucidates, at least partly, their interaction. Still I think that this discussion has somewhat the same faults as our other systems employed to describe the forces involved in the translocation of water from soil by way of the plant towards the atmosphere. The free-energy considerations make it possible to show that the water-movement inside a plant is thermodynamically possible, and as such is a description rather than an explanation. It largely ignores, however, the relative importance of the various component forces involved in this movement. Therefore, if used by itself it might give a wrong impression. As an example, I want to mention the temperature-effect on the water-movement from soil to air. The temperature-gradient from roots to soil will hardly have any effect on the water-uptake by the roots. The temperature-effect here is mainly found in the resistance towards water-exchange. At low temperatures the water-permeability of the protoplasm is so much increased that it may cause almost complete blocking of water-uptake. The temperature-gradient between roots and leaves has no effect at all on the water-movement in the xylem. On the other hand, the temperature-gradient between leaf-cells and surrounding air is one of the main determining factors in transpiration. To express this in terms of equation (34), Δf_p is the determining factor in the water-movement inside the xylem, whereas Δf_σ is more important in the evaporation.

One question to be discussed is whether it is profitable to substitute the free energy and free-energy changes for the terms which have hitherto been used to describe water-relations inside soil and plants. There are two aspects of this problem; one is nomenclatorial, and the other is practical. It is perfectly true, as pointed out, that there is ambiguity in nomenclature. However, it should be pointed out that this ambiguity is not paralleled by one in the meaning of the words, because most authors expressly state that their terms of suction force, suction pressure, suction tension, turgor deficit, etc., are homologous with each other. It is questionable whether the situation would be improved by introducing a new set of terms which admittedly are thermodynamically sounder.

As far as the practical aspects of the problem go, it would be extremely difficult for the plant physiologists to express their values in terms of Δf, because this value depends, among other things, on temperature. Now it is physically almost impossible to maintain constant temperatures in an evaporating system. For this reason it will be necessary in every experiment to make very accurate temperature-determinations in every part of the system. It is much more convenient to use values which are relatively independent of temperature, such as suction force.

A few specific remarks should be made. The conclusion that the drop in free energy of water while passing through the roots was not great, as compared with the total drop in free energy experienced by the water in passing through the entire plant, does not seem warranted. The enormous drop in free energy between leaf-cells and air obscures whatever differences there exist in other parts of the system. Actually I believe that a drop in free energy of the water through the roots is of the same magnitude as the drop inside the leaves and the drop from roots to leaves.

Another point which I question is the statement that the cooling of the upper parts of the phloem-tissue of the plants would tend to slow down or even reverse the direction of movement. We have to do here only with the hydrostatic pressure and the flow within the phloem-system is independent of temperature-gradient within this system.

P. R. WHITE (The Rockefeller Institute for Medical Research)--As I understand Dr. Edlefsen's thesis, it is that the soil scientists and the plant physiologists in certain fields are investigating the same phenomena but speak quite different languages, that both, but especially the plant physiologists, are to be reproached with the ambiguity and lack of precision in their language and that the thermodynamician (if he will accept the title) has a language which is applicable to both, is not ambiguous, and whose adoption by all three would make everything quite clear and understandable.

I wonder if this thesis does not at the very start represent the sort of oversimplification which one often finds when the specialist in one field attempts to apply his specialty to a related but different field.

As Dr. Edlefsen points out, the soil scientist uses such terms as "moisture-equivalent," "hygroscopic coefficient," "capillary capacity," and "vapor-pressure." All of these are physical terms representing static or equilibrium-characteristics of the soil-water system. They take no cognizance of any dynamic characteristics such as those in which the plant physiologist's chief interest lies. The plant physiologist, on the other hand, speaks of "root-pressure," "transpiration-pull," "suction tension," "turgor deficit," and "osmotic pressure." All of these represent physical characteristics of the system, it is true, but characteristics which depend for their magnitude on activities either of the organism itself or of external forces acting through the organism. The phenomena designated with these terms by the plant physiologist are not the same as those referred to by the soil scientist. And I, as a plant physiologist, should object strenuously to Dr. Edlefsen's implication that "turgor deficit," "suction tension," and "effective osmotic pressure" are synonymous. "Turgor deficit" is a characteristic of the cell-contents-cell-wall system in which the physical characteristics of the system as a whole, and considered as an isolated system, are emphasized; "suction tension" is a characteristic of the same system, dependent on the same facts but in which the relationship of the system to external systems is emphasized; while "effective osmotic pressure" is likewise a characteristic of the system in its relation to external systems but in which the role of a particular part of the system, the solvent-solute part, is emphasized. Much of the "ambiguity" to which Dr. Edlefsen objects is due to attempts to use these terms synonymously instead of keeping clearly in mind wherein each one really does differ from each other one. Some physiologists still persist in synonymizing "osmotic value" (a characteristic of an isolated system) and "osmotic pressure" (the expression of that characteristic when placed in contact with one or more contiguous systems). That sort of confusion is particularly irritating to me because of the frequent tendency of some physiologists to use data obtained in transpiration-pull experiments in discussing the validity of secretion-pressure results. They have little or nothing to do with one another.

But, to return to the paper under discussion, can the problems of the soil scientist and the plant physiologist be harmonized and clarified by translating both into thermodynamic terms? Dr. Edlefsen devotes the major part of his paper to the derivation of 39 equations for use in discussing the characteristics of specific free energy as it applies to the soil, the plant, and the air as a combined system. So far as I can see, both the logic and the mathematics of these equations are sound. Many of them represent facts well known to all plant physiologists. Equation (19), for example ($\Delta f = f_B - f_A = -\int_A^B dw_m$), if I understand it correctly, states among other things that, in order that water may be moved from the soil to the top of the plant, work must be done by some agency external to the mere physical (as distinct from biological) entity, the soil-plant-water. This work, the plant physiologist attributes to the living functions of the plant and to the radiant-energy sources outside the plant. The necessity for a source of energy external to the merely physical soil-plant-water system is emphasized and restated in equations (24) to (31).

In equations (34) to (39), the specific free-energy characteristic is analyzed into several components and by application of the several equations thus derived to data taken from the plant-physiological literature, a thermodynamic statement of certain results is presented. Kramer's data applied to equation (35), [$\Delta f = RT \ln (p/p_0)$], shows that in his experiments the major drop in free energy was in the main body of the plant rather than in the roots. Since only a small part of the root was removed, the plant physiologist presents the same facts by saying that the frictional resistance to flow is a function of distance.

Thut's data applied to the same equation indicate that in his experiments practically the entire drop in free energy occurs at or near the leaf-surface, which is another way of stating the old Dixon-Askenazy concept that in an environment conducive to rapid transpiration the major force in bringing about movement of water through the soil-plant system is applied in evaporating the water at the leaf-surface, and that under these conditions forces such as secretion-pressure which may be applied at other points in the system are of relatively minor significance.

I might add that certain of my own findings could also be applied in these equations. I have found, for example, that isolated roots will secrete water under certain conditions against considerable pressure-gradients. The experiments were carried out under such conditions that the root was bathed throughout in free water. At the distal end this contained solutes sufficient to give an osmotic value of about 1.5 atmospheres. The liquid secreted at the proximal end has not been analyzed except for reducing sugar for which it gives a negative reaction. From data obtained on other plants, it seems probable that its osmotic value is somewhat less than that of the solution at the other end, so that whatever osmotic gradient exists would tend to drive water in a direction opposite to that in which it actually moves. The hydrostatic pressure-gradient against which water is known to move is likewise of unknown value but is known to be not less than six atmospheres. If we substitute the known values for P and v in equation (18), ($\Delta f = \int_A^B vdP - \int_A^B dw_m$), we are merely stating in mathematical terms the observation that the free energy of the water secreted in this system is a function of the work done on the system soil-plant-water by some external agent, in this case the living protoplast.

Personally, I fail to see that these equations tell us anything that we did not already know. It seems to me that this is emphasized by the fact that in his final discussion of the "direction of motion of water in the phloem of the plant," Dr. Edlefsen himself falls back on mere ambiguous words instead of using his thermodynamic equations.

All this is not to say that Dr. Edlefsen's contribution is unimportant. I believe that it is important to know something about these equations and to be able to use them in checking the completeness of one's consideration of given problems in biodynamics. But they are important only as a substitute for and control on considerations of common sense. If one has the latter in adequate degree, the equations add little except a new terminology, which may be less easy to misuse, less subject to possible ambiguity, but is neither more precise nor more simple nor more useful than plant-physiological language in the hands (or rather the mouths) of careful and clear-thinking plant physiologists.

N. E. EDLEFSEN (University of California)--In summarizing the comments, space does not permit specific reference to each commentator. The original paper was, of course, not intended to be an exhaustive treatment of the subject, and the references to literature were very meager. It was intended to be merely a skeleton of an adequate treatment of the subject. Its purpose was to provoke discussion.

There were some typographical errors in the original paper to which several of those commenting called attention. These have been corrected. Some other points to which attention was called by the commentators are discussed below.

There seems to be considerable difference of opinion as to the usefulness of the thermodynamic treatment. Some suggested that this is because many investigators in problems related to the use of soil-moisture by plants are not sufficiently familiar with the language of thermodynamics to realize its full significance. The mathematical treatment in the paper was standard and no originality was claimed for it. It was perhaps amplified to greater degree than one usually finds in texts on thermodynamics. This was deliberate, and was done with the hope that it might help to demonstrate to the reader, who is not already familiar with the subject, some idea of the application of thermodynamics to the use of soil-moisture by plants.

Several called attention to an error in the paper wherein it was stated that sugars are manufactured in the phloem-tissue of the leaf whereas a more accurate statement would have been that this process takesplace in the chlorophyll-containing cells. This writer is not familiar with the detailed morphology of the plant, but this in no way changes the reasoning. A number of further illustrations were given by some of the commentators of the application of thermodynamics to the problem under discussion. Some of these were illustrated with data.

Certain points in the discussion can best be summarized by reference to specific commentators.

Crafts seemed to be sympathetic to the idea of introducing more exact language in our dealing with the use of soil-moisture by plants, but cautions that at the present time few people in the field of plant-physiology and soils are sufficiently familiar with thermodynamic language to be able to read such literature. He says that at best, thermodynamics is, for the biologists, merely a tool as a means to an end and not an end in itself. It might be pointed out that it is not necessary to restrict such a statement to biologists. Thermodynamics is only a tool in any science. He cautions against the advisability of suddenly attempting to discard terms which are well established in literature and substitute for them the language of thermodynamics. This is undoubtedly not only inadvisable, but it is very doubtful if it would be possible, even if we thought it desirable, to convert abruptly from one language to another one. He and others refer to the complexity of biological processes and is inclined to feel that many cannot be treated with exact mathematical analysis. He calls attention to the work of Hoagland, Broyer, and Grossenbacher to show how complex and unpredictable the functions of ion-absorption and root-pressure may be. It seems the word, "unpredictable," is an unfortunate choice since it applies to the processes that are not understandable. We have little justification, it would seem, for such a philosophy since our experience has been in all scientific work that when sufficient information is available, phenomena are predictable. It seems that this is merely a demonstration of the fact that we do not at present understand the phenomena. He refers to the water-movement in the phloem as being regulated by water-balance and concentration-gradients. I am not sure what is meant by "water-balance," and would suggest a more precise term. He mentions the complexity of soils and refers to unpredictable changes which may occur in them. Here again, it seems the word, unpredictable, is inappropriate. He says that the primary work of a biologist is to perform a critical experiment. Most everyone would agree with this statement. It would seem, however, that a critical experiment requires a recognition of all factors involved. Experiments are too often conducted in such a way as to oversimplify the phenomenon taking place. This is necessary in many cases just as it is necessary in making a mathematical analysis of a problem to work out the simple cases first, neglecting the variables playing secondary roles. Any attempt, however, to draw generalizations from experimental work on the movement of soil-moisture through plants results in a realization that much of our experimental work has been oversimplified in the sense that some of the variables playing an important role have been neglected.

He refers to the interpretation of the calculations in the paper where it is shown that, under conditions postulated in the calculations, the force moving water up a tree is 1,000 times gravity and refers to the statement of Meyer and Anderson in their text where they say "such a pull (1,000 times gravity) is equivalent to a pressure of about one atmosphere," and also refers to Veihmeyer and Hendrickson's work wherein it was estimated that a force of 16 to 20 atmospheres was required to take moisture from soil at the permanent wilting-percentage. To this he adds two atmospheres to take the water to the top of a tree ten meters high from Dixon's calculations, making a total of 18 to 22 atmospheres, as the force required to carry water to the top of a tree ten meters high. The statement by Meyer and Anderson seems to be incorrect. The fact that 1,000 times gravity in the CGS system is approximately numerically the same as a pressure of one atmosphere in the CGS system is purely coincidental. The quantities are not the same kind; they are not dimensionally the same. This is evident if one uses any other units except the CGS system. It should be remembered that a force of approximately 1,000 times gravity calculated in the paper is the average force per gram of water. The total force tending to move the column of water up the tree is, of course, much greater than this. In fact, under the conditions postulated, it would be approximately 9.4×10^8 dynes. In this connection, it is necessary to keep clear the difference between a surface-force, for example, dynes per square centimeter, and body-force, for example, dynes per gram.

Gardner raises the logical question of the interpretation of the last term in equation (34). Whether one should include the term is probably debatable. It depends, to some extent, on how the function, free energy, is applied. For example, if one wishes to calculate the changes in free energy of a finite system, it would be necessary to include this term. However, it is obviously limited to an interface, and in the body of the fluid if one is thinking of the free energy as a point-function, it would play no role. As Gardner points out, the equation should be made dimensionally homogeneous. To do this, the term ΔF_σ must have the dimensions of force per unit-mass. The right-hand side of equation (39), therefore, has been corrected accordingly. He feels that the term, free energy, is somewhat misleading since the average reader might infer, as have some engineers, that a fluid is capable of doing work because it is under pressure. It is true that one finds in the literature the statement that the fluid has "pressure-energy" if it is under a state of pressure. For example, the term (P/ρ) in Bernouilli's equation is sometimes spoken of as the "pressure-energy" term. As a matter of fact, this term must obviously be used in the analysis of the problem whether it be dealing with hydraulic or with free energy in a more general problem. It must be remembered, however, that if we think of a liquid as having energy by virtue of its being under pressure, we must recognize that we cannot use that "pressure-energy" until it is converted into some other form; and hence, the question occurs as to whether we should even think of it as having energy due to the fact that it is under pressure. This does not need, however, to interfere with our including the term as one of the free-energy terms providing we understand the meaning of it. He feels that "thermodynamic potential" would be a better term to use. It might be pointed out that this term is used in Europe more generally than is free energy, but American authors for the most part have adopted the term, free energy, rather than thermodynamic potential.

Horton questions the advisability of using the word "pull" to designate the force moving water up a tree. The force is due to a field and is directed upward. We are, therefore, justified in using the word "pull" in the same sense as when we say gravity "pulls" down on objects. This infers nothing as to the state of tension or pressure of the water.

Miller thinks it desirable to have a more nearly uniform terminology for many of our facts relative to soil and water, but that it would take too much training for an individual to master the science of thermodynamics in addition to his training as a soils man or as a plant physiologist. He raises the question as to our destination as scientists since we are becoming more specialized in every phase. This raises the question as to whether the adoption of thermodynamic reasoning in the fields of soils and plant-physiology makes the subjects more specialized. I think the reverse is true. The adoption of a more basic interpretation of the experimental results in both fields tends to simplify and coalesce rather than complicate and diverge the two fields. I am here, of course, referring to graduate students and others interested in research-work. The adoption of such a practice might be questionable for the large group of students taking elementary courses in plant-physiology.

Went feels that while there is ambiguity in nomenclature, this is not paralleled by an ambiguity in meaning of words, because he feels that most authors expressly state that their terms of "suction force," "suction pressure," "suction tension," "turgor deficit," etc., are homologous with each other. He feels that it is questionable whether the situation will be improved by introducing a new set of terms even though they are admittedly more thermodynamically sound. This seems to be in contrast to White's view-point when he states that he objects strenuously to the implication made in the paper that "turgor deficit," "suction tension," and "effective pressure" are synonymcus terms. White feels that much of the "ambiguity" referred to in the paper is due to attempts to use these terms synonymously instead of keeping clearly in mind wherein each one really does differ from each other one. White admits, however, that confusion does exist in plant-physiology literature.

Went refers to the fact that free energy depends on a number of things including temperature and refers to the difficulty in measuring this quantity accurately for all parts of the plant in certain experimental procedures. He thinks that the suction force is relatively independent of temperature. He does not feel that one is warranted in saying in the conclusion that the drop in free energy of water while passing through the roots, as discussed in the paper, was not great as compared with the total drop in the free energy experienced by the water in passing through the entire plant. The data used do indicate this, but one might, of course, question the data. He questions whether a cooling of the upper part of the phloem-tissue of the plants would tend to slow down or even reverse the direction of movement. I am not familiar with any experiments wherein measurements on this movement have been made with a specific purpose in mind of answering this question; I can only offer conjection on the point. Certainly a reversal in temperature would tend to reverse the direction of flow and certainly a lowering of the temperature would increase the viscosity of the solution. This would tend to indicate that one might, under these conditions, get a reversal. The force tending to produce motion of the water can, as pointed out by Veihmeyer, be calculated under specified conditions.

White fails to see that the equations tell anything that we do not already know, and thinks that they are important only as a substitute for and control on considerations of common sense, and feels that if one has the latter in adequate degree, the equations add little except terminology. He thinks that the language of thermodynamics is neither more precise nor more simple nor more useful than plant-physiological language in the hands of careful and clear-thinking plant physiologists. From a review of the literature, however, and comments in this report, it is evident that confusion does exist among those interested in the use of soil-moisture by plants. It is hazardous to say that one group has common sense and the other one does not. The language of mathematics and thermodynamics is only a tool and helps in analysis because most of us have not common sense in adequate degree, and neither have we mental ability to carry in our minds the detailed reasoning which is necessary in the analysis of complicated problems such as one finds in connection with the use of soil-moisture by plants as well as other soils and plant-physiological problems. Many, therefore, find the thermodynamic reasoning helpful.

REPORT OF COMMITTEE ON INFILTRATION, 1940-41

G. W. Musgrave, Chairman

During the past year there has been a very great increase of interest in the subject of infiltration and considerable activity, both in the application and investigative phases of it. The activity of several governmental agencies which are concerned with national flood-control problems has been extensive and included both infiltration-surveys of watersheds and extensive analyses of hydrographs which were particularly applicable to the problem at hand. As so often is the case, it has been difficult to keep the investigative phases abreast of the very real needs of the various action agencies.

Nevertheless, there were certain very definite accomplishments in the research phases of the problem. The present program includes four papers on infiltration, namely, those of L. K. Sherman, H. G. Wilm, Hubberty and Pillsbury, and J. G. Montes. Work reported elsewhere by Moore indicates that the effect of temperature on infiltration is much more complex than is generally supposed and leads to the very important point that temperature may have certain effects upon the soil as well as upon the viscosity of water. It would seem likely that under certain conditions a rise in temperature, decreasing the viscosity of water might be compensated in whole or part by dispersing effects upon soil-structure or even by increased viscosity due to increased solvent power of the water. The seasonal curve is very similar to that reported for Edwardsville, Illinois, by Horner and Lloyd. As noted in the last report of this Committee and as confirmed by work of the present year, high summer temperatures are normally correlated with low soil-moisture so that the seasonal-variation curve (if we assume that yet other factors are not large) quite probably is the resultant of two variables which are negatively correlated with each other.

LANGBEIN has provided the Committee with information on the researches of the Geological Survey during the past year, stating:

"Studies have been made of the rainfall- and runoff-relations of Strawberry Creek in the San Bernardino Mountains for the purpose of determining quantitative indices of the absorptive qualities of the ground. The few evidences of sheet-erosion contrasted with the deeply eroded runnels and channels suggest that there is apparently very little surface-overland flow, and except for surface-interception and direct evaporation most of the rainfall is infiltrated and flood-runoff is discharged from the zone of aeration. It was found that the portion of rainfall during a storm that is absorbed and retained as field-moisture and ground-water increments varies greatly with antecedent conditions. The antecedent field-moisture apparently provides a suitable index of the absorptive conditions. For example, it was found that a storm of five-inch precipitation with only three inches antecedent field-moisture would produce only 0.08-inch runoff and with 24 inches antecedent field-moisture, 2.0 inches of runoff. Antecedent field-moisture ranged between 3 and 27 inches, a wider range than in storm-precipitation, of which the maximum during the period of record was 18.5 inches. When antecedent conditions are dry the absorptive capacity is so large that only 1.5 inches of an 18.5-inch rain may run off. When conditions are wet, this runoff can be obtained with but 3.7 inches of precipitation. In contrast with the humid regions where rainfall is nearly uniform month to month and field moisture-conditions do not fluctuate widely, in Southern California antecedent conditions as they affect the absorption and retention of rainfall are paradoxically of greater influence on runoff-volumes than the rainfall itself. The correlation between rainfall-intensities and runoff-volume, although detectable was very weak.

"Other studies were begun early in 1940 and are still in progress in New Jersey for determining the absorptive qualities of urban, suburban, and rural areas. Results thus far indicate significant and measurable differences in behavior, but not as much as the density of buildings on an urban drainage in Newark would at first suggest. No storm produced 100 per cent runoff as an impervious area would require. Moreover in even this completely urban area there was considerable variation in absorption depending on antecedent conditions and seasonal effects."

During the past year **HARRY F. BLANEY** of the Division of Irrigation, Soil Conservation Service, in connection with consumptive use of water-studies on the Pecos River in New Mexico and Texas conducted some water-application efficiency-studies in irrigated areas by soil-moisture methods. Soil-sampling indicated that in some areas the irrigation-water did not penetrate into the soil below six feet and that the amount of water absorbed varied from 25 to 76 per cent of the water applied. The percentage of water absorbed ranged from 32 to 46 in corn land (silt-loam soil), 67 to 70 in orchard (fine-sand soil), 25 to 76 in cotton land (fine sandy loam-soil), and 26 to 65 per cent on alfalfa (fine sandy loam-soil).

In connection with recent water-supply and irrigation-studies in Cuba, Mr. Blaney reports that **JOSÉ GARCIA MONTES**, President of Cuban Society of Engineers, has made some interesting studies on infiltration. The results of the investigation are described in a paper "Un escurrimetro aparato util en la hidrologia agricola" published in the Proceedings of the First National Congress of Cuban Engineers.

The soils of Cuba present an excellent opportunity for infiltration-studies. In the United States the clay-content of a soil usually does not exceed 65 per cent, while in Cuba large areas contain more than 75 per cent and some exceed 90 per cent of clay-particles. H. H. Bennett and R. V. Allison in a report "The soil of Cuba" point out that Matanzas red soil, although containing in places more than 90 per cent clay, is so open-natured that it frequently takes up and rapidly disposes of nearly the entire rainfall, which in places exceeds 70 inches annually.

M. R. LEWIS states:

"Successful application of irrigation-water is obviously a matter of securing the infiltration of the proper quantity of water uniformly over the whole of an irrigated field. In general, heretofore, no direct measurements of infiltration-rates have been made preliminary to the design of irrigation-systems. In lieu thereof, soils have been classified in general terms as to texture and the systems designed according to the experience and judgment of the engineer or farmer. In numerous cases infiltration-rates have been out of line with those expected and readjustments have been required. In some cases these readjustments have been extremely slow and the success of project or farms has been impaired or prevented.

"Specifically, data on infiltration-rates of all sorts of soils are needed for the following irrigation-problems:

"(1) Transmission-losses in earth-canals and laterals. (Data on the effect of depth, velocity, colloid-content of water, age of canal, vegetation, etc.)

"(2) Design of lateral system. (Data leading to information of size of irrigation-stream required by individual irrigator.)

"(3) Preparation of land for irrigation. (Data leading to information on size of stream and length of runs required.)

"(4) Application of water. (Data on uniformity of infiltration-rate over the area, absolute rate of infiltration when all or different portions of the soil-surface are covered with water at different depths, change of rate of infiltration as affected by length of time of application, moisture-content at beginning of application, etc.)

"(5) Various research problems. (Effect of infiltration-rate on erosion, best shape and size of furrows, spacing of furrows and corrugations, alternate versus every furrow irrigation, etc.)

"There is considerable question as to whether the present methods of measuring infiltration-rates by means of tubes or small plots give absolute rates that can be applied over irrigated fields. Except for the comparatively small areas irrigated by sprinkling, data secured from natural or artificial rainfall-studies are probably of little or no value in irrigation-practice. There is, therefore, need for research on methods before the needed data, as outlined above, can be secured. Until these data are accumulated, the design of irrigation-systems and the application of irrigation-water will remain an art instead of a science."

G. A. HATHAWAY points out:

"One phase of the problem that appears important at the present time is the relation of infiltration to the problem of airport-drainage, particularly turfed areas, and the distribution, spacing, and type of tile or other types of drains that are designed to maintain the water-table at a definite elevation.

"There is, of course, the recognized need of securing the proper relation between infiltration-data secured from plots and small watersheds and infiltration-values for the larger drainage-areas."

As a by-product of the extensive work which has been done by many agencies during the current year, it is most probable that there is a considerable body of information which has not yet reached the tangible stage of publication. This includes not only the experience of certain limitations in the application of the infiltration-theory but also a more general comprehension of the field so that its various specific phases are brought into sharper focus. A more specific view of the problem gives rise to an expression of need for increased research-activity which may be directed toward certain problems or to the application of the infiltration-concept to specific fields.

Data on infiltration-rates for different environmental conditions and different soils in various portions of the United States are being accumulated by a great many branches of the Government, including both Federal and State as well as upon occasion by some minor subdivisions. Where adequate rainfall- and runoff-records are being obtained there ordinarily is opportunity to develop infiltration-rate curves. Often in connection with irrigation by flooding, a similar opportunity exists. In addition to these opportunities--which are not by any means completely utilized--there are many investigations in progress by various research-agencies that are directed primarily toward some phase of the subject of infiltration. Because of these activities there has been marked progress in our knowledge during recent years as Horner and Jens have recently pointed out. Nevertheless, there is a continuing need--indeed an increasing pressure for factual evidence--on many phases of the subject, the importance of which is increasingly recognized.

U. S. Soil Conservation Service,
Washington, D. C.

REPORT OF COMMITTEE ON RAINFALL, 1940-41

Merrill Bernard, Chairman

The Committee has lost one of its active members in the resignation of Miss Mary O. Soroka, while acquiring a new member in the acceptance of Ing. Andrés García Quintero, of the Hydrologic Service of Mexico.

The following progress in the observation and analysis of rainfall-data is reported:

Rainfall-observation stations--Precipitation-stations were established during the year under the cooperative program between the Weather Bureau, the Corps of Engineers, and the Department of Agriculture:

Hydrologic Region	Recording	Non-recording
Albany, New York	45	1
Albuquerque, New Mexico	72	34
Cincinnati, Ohio	136	59
Fort Worth, Texas	210	111
Iowa City, Iowa	92	31
Kansas City, Missouri	208	31
Macon, Georgia	66	25
Portland, Oregon	78	..
San Francisco, California	156	..
Total	1,063	292

This brings the total number of recording and non-recording stations in the program to about 1,400 and 300, respectively. In addition to the recording stations operated by the Bureau there are about 700 additional records included in the hydrologic bulletins from gages owned by other agencies. Also, during the year there were approximately 250 cooperative stations added to the climatological network of the Bureau.

Organization of storm-rainfall--Under cooperation between the Corps of Engineers and the Hydrometeorological Section of the Weather Bureau about 400 of the approximately 1,400 storms of record were analyzed. The work of assembling the data and plotting mass-curves and isohyetal maps of rainfall is being conducted in the field offices of the Corps of Engineers after which the data are submitted to the Hydrometeorological Section for review and modification affected through meteorological analysis.

Hourly rainfall-data--Tabulations of rainfall in hourly amounts observed at all first-order stations of the Weather Bureau for the whole period of record are being made under a Works Progress Administration Project at Pittsburgh. The compendium will embrace approximately 7,500 station-years of record.

Hydrologic research-projects--Several agencies within the Department of Agriculture are compiling rainfall-amounts for shorter intervals from station-records in selected areas. The Soil Conservation Service reports 38 projects in 22 stations on which rainfall-data are being gathered. On these projects gage representation is carried as high as one gage to one-half square mile. Studies of size and velocity of rain-drops are also being conducted in the Soil Conservation Service hydraulic laboratories.

The micro-climatic studies of the Soil Conservation Service on the Muskingum Basin in Ohio are continuing.

In connection with flood-control surveys the Department of Agriculture has compiled and analyzed the available precipitation-data applicable to the drainage-basins under survey. To calculate runoff from relatively minor, as well as capital floods, requires precipitation-data broken down into short time-intervals. Intensity-records tabulated by natural breaks in intensity by five-minute intervals greatly increase the accuracy with which runoff can be calculated for the sub-drainage basins. On these basins the floods of lesser magnitude are frequently caused by very brief bursts of high-intensity rainfall. To meet these problems rainfall-records are analyzed and precipitation-excess curves prepared for each recording station. The dimensionless form of this curve in which the ratio of intensity to maximum (or average) intensity is plotted against the ratio of precipitation-excess to total precipitation has proved useful on those basins with sparse records.

A number of worthwhile technical papers have been published throughout the year, among them that by Katharine Clarke-Hafstad entitled, "Reliability of station-year rainfall-frequency determinations." This paper has evoked considerable discussion and should become the means of clarifying an understanding of the station-year method of determining rainfall-frequency.

U. S. Weather Bureau,
Washington, D. C.

REPORT OF COORDINATING COMMITTEE ON HYDROLOGY BETWEEN THE AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS AND THE AMERICAN GEOPHYSICAL UNION, 1940-41

H. S. Riesbol, Chairman
(Presented by title)

The Committee wishes to call to the attention of members of the Section of Hydrology, American Geophysical Union, the following projects that are being worked on by members of the Committee on Hydrology of the American Society of Agricultural Engineers.

(1) The Index entitled, "Instruments commercially available for use in the study of hydrology and meteorology" was discussed in the 1940-report of this Committee. This Index has been brought up-to-date by Mr. Pomerene, member of the Committee on Hydrology.

(2) A survey is being completed by R. B. Hickok of the Committee on Hydrology, to establish the specific needs of agricultural engineers for hydrologic information. Numerous replies have been received from a questionnaire sent to engineers engaged in drainage, irrigation, flood-control, water-supply, soil- and moisture-conservation work, etc., in regard to the type of hydrologic information required for the solution of their problems and to the deficiencies now existing in available agricultural hydrologic data. These replies are being summarized and analyzed by Mr. Hickok for presentation before the annual meeting of the American Society of Agricultural Engineers in June, 1941.

(3) David W. Cardwell, member of the Committee on Hydrology, has started work on a survey to determine desirable forms for the reporting of hydrologic data for greatest utility to agricultural engineers in their various fields of application. This survey will supplement and complete the information being collected by Mr. Hickok [see (2) above]. For example, the survey described under item (2) may determine that engineers are particularly in need of runoff-data from certain watershed-types, while this survey may discover that they are more interested in receiving these same data in the form of peak-rates of discharge, volumes of runoff, times of concentration, etc. The survey is being carried to extension engineers and professors of agricultural engineering in the State colleges, to regional engineers of the Soil Conservation Service and United States Forest Service, to district engineers of the Bureau of Public Roads, and similar groups.

Agricultural engineers and other agriculturists engaged in hydrologic work are concerned with the lack of uniform and clearly understandable definitions for the ever increasing number of terms belonging to the field. Outstanding examples of confusion are: "Losses", a term used by the engineer to denote precipitation which fails to appear as stream-flow and also used by the agriculturist to denote precipitation which does not enter and remain in the soil for use by crops; and "infiltration", a term often used by engineers to denote storm-precipitation which does not appear in the hydrograph of runoff and also used by agriculturists to denote water passing through the soil-surface at a specific point into the zone of areation. These are only two examples of a large number of similar cases.

The longer an attack upon this problem is delayed the more difficult will be its eventual solution. As a Joint Committee between two scientific and professional societies which represent pure science versus applied and engineering versus agricultural, it seems logical that we should initiate and promote activities along this line. It is noted that the Water Resources Committee of the National Resources Committee in their publication "Deficiencies in basic hydrologic data" published in September, 1936, made the following statement concerning this problem:

"(1) The Committee has been handicapped in its work by the lack of generally accepted standards of nomenclature and units of measurement as applied to hydrologic data.

"(2) The several attempts made in the past to establish such standards reflect clearly the need for them. Reports and recommendations have been made by committees of the American Society of Civil Engineers, the Boston Society of Civil Engineers, the American Geophysical Union, and other organizations, but none of these reports has been widely adopted.

"(3) To prepare a comprehensive and authoritative report on the standardization of hydrologic nomenclature and units of measurement is not a task for a few weeks or a few months, but rather one for a competent committee during a period of a year or more. It requires a fairly large, capable, special committee acting under Federal auspices and authority. Such a committee should have as advisory associates, representatives of national technical societies concerned with hydrological studies, such representatives being designated by their respective societies when the latter have been invited to cooperate. This matter is sufficiently important to warrant its sponsorship as a special project by the National Resources Committee, and we recommend the appointment of such a special committee under the auspices of the Water Resources Committee of the National Resources Committee."

It is, therefore, the recommendation of this Committee that the American Geophysical Union and the American Society of Agricultural Engineers render every possible assistance to the Water Resources Committee in the establishment and appointment of a Special Committee to Standardize Hydrologic Nomenclature, Units, and Definitions. It is also our recommendation that the Special Committee include representatives of the American Geophysical Union, the American Society of Agricultural Engineers, the American Society of Civil Engineers, the Soil Science Society of America, the American Society of Agronomy, and the Society of American Foresters, if these organizations are interested in participating in this work. Any other interested and recognized professional group should also be allowed to participate.

Soil Conservation Service,
Coshocton, Ohio

REPORT OF COMMITTEE ON UNDERGROUND WATERS, 1940-41

David G. Thompson, Chairman

The membership of the Committee during the past year has continued as it was a year ago [see Trans. Amer. Geophys. Union, p. 433, 1940].

During a large part of the year, particularly during the last few months, many of the members of the Committee have been engaged in activities more or less closely related to defense. As a consequence it has been necessary to omit or postpone some research studies that might otherwise have been carried on, and the following report is briefer than usual.

A report on research on hydrology and physiography of limestone terraces, by Dr. A. C. Swinnerton, is published as Appendix A of the present report.

Dr. WILLARD GARDNER reports as follows in regard to hydrologic studies at the Utah State Agricultural College:

"We have continued model tests of streamline motion of water into drains for varying boundary-conditions and Dr. Kirkham presented another paper at the recent meetings of the Soil Science Society of America in Chicago, "Pressure distribution and streamline flow into the drains in water-logged land overlying an impervious layer". Dr. Kirkham recently accepted a research position with the United States Navy but we plan to continue these model tests another year.

"In particular, we had hoped to test the case of flow of water into a well extending through a horizontal stratum with varying amounts of hydrostatic pressure in the stratum. The Darcy velocity-law provides a formula for this case and a model test would provide a starting point for the investigation you suggest regarding artificial recharge by means of wells."

HARRY F. BLANEY has furnished the following statement in regard to investigations relating to ground waters with which he has recently been connected:

"A report on a study of consumptive water-use and requirements, made by the Division of Irrigation of Soil Conservation Service, in connection with the Pecos River Joint Investigation, New Mexico and Texas, has been completed; also a report on drainage in the Lower Pecos River Valley in Texas has been prepared. Both of these reports include data on ground-water as related to irrigation and drainage, and they will be published by the National Resources Planning Board in 1941.

"Ground-water studies in Beaumont and San Jacinto valleys have been continued by the Division of Irrigation in cooperation with the Metropolitan Water District of Southern California and the State of California, Division of Water Resources, and results given along with consumptive use of water-data in a progress-report entitled "Utilization of the waters of the Beaumont Plains and San Jacinto Basin, California", issued February 1941.

"In connection with a recent irrigation-study in Cuba, I inspected some wells near Isabel in the southern part of the Province of Matanzas, where the depth to ground-water varied from 15 to 20 feet and the water-supply was abundant. Four wells within a radius of 2,000 feet were being pumped at the rate of 2,500 to 9,600 gallons per minute, with a three-foot drawdown."

C. E. RAMSER, Chief, Hydrologic Division, Soil Conservation Service, has reported briefly as follows in regard to activities of the Service:

"The Hydrologic Division of the Soil Conservation Service is continuing the study of the fluctuations of ground-water levels in a number of wells on the experimental watersheds at Cochocton, Ohio, and Waco, Texas. These ground-water studies are being made along with studies of runoff, land-use, and the conservation of soil and moisture."

E. N. MUNNS, Chief, Division of Forest Influences, of the United States Forest Service, has furnished the following report in regard to ground-water studies by that Service:

"The United States Forest Service carries on a restricted program of observations on shallow ground-water levels at its experimental forests and ranges. These observations are made as part of the studies of the influence of forest and range-vegetation on stream-flow and soil-stability. These are carried on not as a study of ground-water itself but as an aid in explaining and interpreting difference in stream-regimen associated with several treatments or conditions of watershed-lands.

"For the most part the observation-wells are located close to control-sections where streamflow is measured. The number of wells at any control ranges from one to five. For example, at the Coweeta Experimental Forest near Franklin, North Carolina, maintained by the Appalachian Forest Experiment Station, Asheville, North Carolina, one series of wells constitutes a cross-section of a mountain valley. Another series occupies a cove or small valley near a ridge top. Elsewhere only a single well in the valley-fill or on the lower slope might be maintained.

"The experimental forest where ground-water observations are made are listed below: Manitou Experimental Forest, Colorado; Fraser Experimental Forest, Colorado; Holly Springs (Chewalla) Work Center, Louisiana; Irons Fork Experimental Forest, Louisiana; Coweeta Experimental Forest, North Carolina."

Activities of the Division of Ground Water of the United States Geological Survey continue to increase as the need for investigation is felt in more and more areas. As of April 30, 1941, investigations in cooperation with States, counties, or municipalities, were being made in 31 States, namely in Alabama, Arizona, Arkansas, California, Connecticut, Florida, Georgia, Indiana, Iowa, Kansas, Louisiana, Massachusetts, Michigan, Mississippi, Nebraska, New Jersey, New Mexico, New York, North Carolina, North Dakota, Ohio, Oklahoma, Oregon, Pennsylvania, South Dakota, Tennessee, Texas, Utah, Virginia, Washington, and Wyoming, and the Territory of Hawaii. The annual report on measurements of ground-water levels and artesian pressures for 1940 is being published in six volumes and will contain records for wells in 38 States and the Territory of Hawaii and the District of Columbia. In nearly every one of the many cooperative investigations referred to, new data of scientific value are obtained. It is not possible to list all of these, but a few particular phases of the work may be mentioned.

In the 1940-report of this Committee reference was made to observations in regard to fluctuations of water-level caused by earthquakes. During the summer of 1940 additional information in regard to fluctuations during earthquake was sought from all field-men of the Geological Survey who were operating water-level recorders on wells. The results of this inquiry were summarized in a brief paper presented by your Chairman at the meeting of Section E of the American Association for the Advancement of Science at Philadelphia in December, 1940.

It was found that fluctuations of water-level caused by earthquakes are much more common than had previously been revealed. For example, it was found that the Imperial Valley, California, earthquake of May 18, 1940, was recorded in 44 of 181 wells in the United States and Hawaiian Islands that were equipped with automatic recorders. One well, near Miami, Florida, showed a greater fluctuation for this earthquake than many wells in the Los Angeles Area. This same well, which appears to be especially sensitive to earthquake-shocks, showed a fluctuation of about 0.2 foot as the result of an earthquake on December 21, 1939, whose epicenter was in latitude 2° south, longitude 122° west, on Celebes Island, in the Dutch East Indies. The distance over the surface from the observation-well to the epicenter was 10,180 miles, which is the greatest distance at which fluctuations of water-level caused by earthquakes have been observed. The disastrous Turkish earthquake of December 26, 1939, was recorded at Honolulu, 8,100 miles from the epicenter. This earthquake caused a fluctuation of 1.18 foot in a well at San Antonio, Texas. Some of the details of fluctuations of water-level in wells in Southern California caused by earthquakes are described in a paper by G. A. LaRocque, entitled, "Fluctuations of water-level in wells in the Los Angeles Basin, California, during five strong earthquakes, 1933-1940", which was presented at the May 1941 session of the Section of Seismology of the American Geophysical Union, and is published in the present Transactions [pp. 374-386].

In general, the fluctuations seem to be best recorded in wells where artesian conditions exist. There is some reason to believe that the sensitivity of response of the water-level in wells to earthquake-shocks depends upon the permeability of the materials penetrated by the wells, the fluctuations being greatest in materials that are highly permeable. Further study is to be made of this subject. One need in this study is a type of water-level recorder with a very large time-scale comparable to that of seismographs.

Problems of contamination of fresh ground-water by salt water continue to increase in number and importance as the use of ground-water increases in coastal areas or inland areas, where connate salt water is present. On April 30 and May 1, 1941, the Division of Ground Water of the Geological Survey held a conference in Washington on salt-water problems. Twenty-eight brief papers were presented in regard to many phases of salt-water contamination. One of the most detailed and significant studies of salt-water contamination has been that in the Miami Region of Florida, where, over a large area the fresh-water table is no more than a few feet above sea-level. A report on this investigation, by W. P. CROSS, S. K. LOVE, G. G. PARKER, and D. S. WALLACE, was released on March 29, 1941.

The danger of contamination by salt water of the potable ground-water supplies of the Hawaiian Islands has been recognized for some time and the problem has been rather thoroughly investigated. One method of avoiding the danger of salt-water contamination suggested by H. T. Stearns in 1934 was the use of the so-called Maui-type well [H. T. Stearns, Supplement to geology and ground-water resources of the Island of Oahu, Hawaii, Territory of Hawaii, Div. Hydrog., Bull. 5, pp. 6-7, 1940]. This consists of a shaft that extends slightly below the main water-table, and derives its water either from shallow wells drilled in its bottom, or from an infiltration-tunnel which may also be supplemented by vertical drilled wells. The system is designed to skim the fresh water from above the salt water without producing any great drawdown, and hence uprising of the salt-water content, such as occurs when water is pumped from individual deep wells. So successful has been this practical application of long-known scientific principle that during the past year the Honolulu Board of Water Supply has recommended the construction of Maui-type wells, instead of the usual old type wells, for its public supply-system.

During the past year your Chairman has also served as a member of the Program Committee of the Society of Economic Geologists. In this capacity he solicited papers for a session of a joint meeting of the American Institute of Mining and Metallurgical Engineers and the Society of Economic Geologists, in New York on February 18, 1941, devoted to problems in engineering, geology, and ground-water. At this meeting the several papers, relating more or less to underground waters, were presented. Brief abstracts of these papers were published in the February, 1941 issue of Economic Geology.

As usual, during the year abstracts of papers and reports relating to ground water were prepared by members of the Division of Ground Water of the United States Geological Survey, for publication in the Annotated Bibliography of Economic Geology. Eighty-nine of these abstracts were also submitted for publication in the Bibliography of Hydrology for 1940, United States of America, sponsored by the International Association of Scientific Hydrology.

U. S. Geological Survey,
Washington, D. C.

APPENDIX A--RESEARCH ON HYDROLOGY AND PHYSIOGRAPHY OF LIMESTONE TERRANES

A. C. Swinnerton

Although the past year has seen several important contributions published there is a notable amount of substantial work still in progress. Notations on all investigations, so far as they have come to my attention, are here reported.

Ground-water investigations of the United States Geological Survey have been continued in the Miami Area in Florida, and progress is being made in the coastal area of Georgia and northeastern Florida in obtaining data concerning the capacity of the Ocala limestone. During the past season ground-water investigations by C. W. Carlston were started in the Cretaceous area of Alabama which includes the Selma chalk.

Samples of water from the Ocala formation show an appreciable difference in the calcium-sulphate content in different parts of Florida. In general, the calcium-sulphate content increases with the increase in distance from recharge-areas.

Unusual permeability data are being obtained in the Ocala areas. Of these V. T. STRINGFIELD writes: "Few, if any of the wells drilled into the Ocala are dry. It is not unusual for the larger wells to yield more than 1,000 gallons a minute and a yield of 7,500 gallons a minute with a drawdown of only nine feet has been recorded for one well. The Ocala is the principal source of ground-water in the coastal area of Georgia where it yields to wells in the six counties bordering the coast more than 80 million gallons a day, of which about 70 per cent is in Savannah and Brunswick. It is the source of some of the large springs in Florida and Georgia, the largest of which is Silver Springs, near Ocala, the flow of which has ranged from about 340 million to 800 million gallons a day.

"Observations indicate that the limestone will transmit at Savannah, Georgia, about 250,000 gallons of water a day through each mile width of the formation for each foot per mile of hydraulic gradient. This means of course that with a hydraulic gradient of ten feet per mile, which is comparable to some of the gradients in the Savannah Area, each mile width of the formation will yield 2,500,000 gallons a day.

"Observations at Brunswick, Georgia, where the withdrawal of water from the limestone is about the same as that at Savannah, indicate that the rate at which the limestone will transmit water is several times that at Savannah.

"Other differences in the permeability of the Ocala in other areas have been observed. It is evident that the permeability in areas where the formation is at or near the surface, as in Marion County, Florida, is much larger than that where the formation is deeply buried, as in the southern part of Florida. Also the permeability of the Ocala tends to decrease as the distance from the recharge-areas increases.

"Although not as extensive as the Ocala formation, limestones of Pleistocene and Pliocene ages in Dade County, Florida, are notable for their permeability. Observations indicate that these formations will transmit at Miami about three millions gallons of water a day through each mile width of the formation with a hydraulic gradient of one foot per mile or about 12 times the capacity of the Ocala under the same gradient at Savannah."

The high seismic sensitivity of the wells around Miami, Florida, reported by David G. Thompson at the meetings of Section E of the American Association for the Advancement of Science in Philadelphia may be attributable to the high degree of permeability of these very porous formations.

H. E. ROTHROCK reports the geologic activities of the National Park Service: "Crystal Cave in Sequoi National Park has been studied by Park Naturalist Oberhansley with a view to interpreting it to the visiting public. Further work has been done in the investigation of the New Discovery passages of Mammoth Cave National Park. Dr. Ross A. Maxwell visited the caves of Slaughter Canyon in Carlsbad Caverns National Park in connection with the proposed operations for mining guano there."

In May the Tennessee Valley Authority published Technical Monograph 47, Engineering Geology of the Tennessee River System, under the editorship of Edwin C. Eckel, Chief Geologist. The geological work of nine reservoir-projects id described. This volume is of interest to students of limestone hydrology since approximately half of the total Tennessee Valley Authority area is underlain by limestone. The detailed results, made possible by careful observation and unexcelled facilities for study, make the monograph a most valuable contribution.

B. C. MONEYMAKER is continuing his study of sub-river solution cavities in the Tennessee Valley Area. A paper on his findings thus far appeared in the Journal of Geology [v. 49, pp. 74-86, 1941]. At localities where structural and lithologic conditions were favorable, cavities were reported at depths in excess of 100 feet below the water-table. "Channels are most numerous, largest, and extend to greatest depths in zones of deformation and especially where the movement of ground-water is unimpeded by insoluble or impervious beds" [Op. cit. p. 86].

At the Kentucky Dam site at Gilbertsville, Kentucky, ROGER F. RHOADES reports geologic and hydrologic conditions as follows: "A period of extreme weathering which may have started at the close of the Paleozoic in this region (the time of land-emergence)....certainly culminated just prior to the deposition of the upper Cretaceous gravels of the Tuscaloosa formation..... The general bed-rock decomposition of this period of weathering was laterally extensive and..... locally very thick (up to 350 or 400 feet)....[Cf. Bull. Geol. Soc. Amer., v. 51, p. 1940, 1940].

"....The ground-water flow here (in bed-rock--Fort Payne chert) is mainly along vertical joints and the solution which results enlarges laterally between the chert-layers. As cavities enlarge sufficiently, the intervening chert-layers collapse and the clay and chert slump down and compact to fill the channel, obstructing the upper paths of flow and forcing the water to adopt ....the next lower path. By the successive operation of this effect, the solution is forced lower and lower along the joint. The solution, of course becomes successively slower as the process continues. We feel that we have definitely established this picture.

"We are at present engaged in the treatment of an intense zone of solution which has considerable width and extends down to elevation 70 feet (the River is at 302 feet). The treatment consists of making....excavations....using 36-inch and 48-inch core-drill holes as entrance shafts. Each hole is drilled until cavities are encountered, the cavity cleaned out and backfilled with concrete. This concrete is then drilled through and the boring continued down to the next lower cavity.... Excavation in the dissolved areas extends laterally to intersect the adjacent borings on either side; in this way a continuous concrete wall, 70 feet long, is being placed underground across the zone of solution....

"We are carefully drawing each step in these operations and a picture is forming of the entire zone of solution, from top to bottom and from one side to the other, showing all the rock-, clay-, and chert-relationships. I believe that we have an unparalleled opportunity to see the inside of a solution zone and we are observing and drawing it meticulously...."

The Geological Survey of Missouri has in preparation a report on the springs of Missouri.

Major WALTER B. JONES at Camp Livingston, on leave from the Alabama State Geological Survey, reports: "For a number of years a group of us have been doing some work in Alabama caves and caverns. We are keeping as complete a record as possible of all our work, including sketches of the underground plan of the caves, height of roof, character of roof and floor; photographs of interesting features inside and outside; estimating the flow of water at various seasons of the year and in various parts of the cave; collecting and studying cave-faunas which are giving some indication of the extent of the underground passages and their relationships one to another; and gaining such other information as we could get.

"During the past year we have studied 24 additional Alabama caves, running the total number to 86.... We have evidence of at least 50 additional caves.... Study of cave-faunas is progressing satisfactorily."

During 1940 the Speleological Society of the District of Columbia reorganized to form the National Speleological Society. Its purposes as stated in its constitution are "to promote interest in and to advance (in) any and all ways the study and science of speleology". Membership is composed of those whose interests are the study of speleology or exploration of caves". Dues are three dollars a year. The principal activities consist of occasional meetings and a great many study and exploratory trips to cavern areas. The current winter program lists eleven trips to localities in Pennsylvania, Virginia, Maryland, and West Virginia. It is planned that the field-work of the Society will be expanded as groups of members are formed in various other localities. A library, bibliography, and collections of photographs and maps, all of these initiated by the District of Columbia Society, will be maintained and it is hoped that a sufficiently increased membership will justify the publication of a quarterly bulletin. Obviously certain phases of the work of this Society will be of great interest and value to hydrologists. Information regarding the Society may be obtained from W. J. Stephenson, 4912 43rd Place, N. W., Washington, D. C.

After studying more than 100 caverns in 15 states, J. HARLEN BRETZ has in preparation a paper "Vadose and phreatic features of limestone caves". During the past year he and his students have mapped instrumentally Cave of the Mounds and Horseshoe Bay Cave in Wisconsin and Mark Twain Cave in Missouri. In the summer Bretz published "Solution cavities in the Joliet limestone of northeast Illinois" [J. Geol., v. 48, pp. 337-384, 1940] in which he contends that the structures of the cavity-fillings in the limestone by the overlying shale belie the interpretation of the cavities as a "fossil" karst. Instead, solution and filling went on contemporaneously. After the shale was deposited, at a time when circulation of ground-water was established in the limestone, the shale broke down into the solution-cavities as they were forming.

The geologic mapping of the Kentucky quadrangles near Mammoth Cave by E. R. POHL, reported last year, is progressing. A paper by Pohl on vertical shafts in limestone caverns has been submitted for publication.

In the Black Hills area, E. L. TULLIS is studying the crystal linings of the caverns and the red crystalline-limestone immediately underlying the crystal linings. He has also investigated a recently opened cave. In 1938 FRANK NEIGHBOR mapped eight caverns in the Black Hills with instruments and on a relatively large scale. His results are available as yet only in manuscript form.

W. ARMSTRONG PRICE is investigating various types of caliche in the southwestern United States. He has also canvassed the subject in the literature for large parts of the world's arid regions. He reports that the surficial calcareous blankets in many of these areas show karst-effects, particularly where the water-table lies well below the capillary up-rise. A manuscript has been submitted for publication covering the material of the two papers he presented at the Austin meetings of the Geological Society of America [Bull. Geol. Soc. Amer., v. 51, pp. 1838-1939, 1940].

Other papers less hydrologic in nature: L. C. Huff, Artificial helictites and gypsum flowers [J. Geol., v. 58, pp. 641-659, 1940]; J. F. Smith, Jr. and C. C. Albritton, Jr., Solution effects on limestone as a function of slope [Bull. Geol. Soc. Amer., v. 52, pp. 61-78, 1941]; R. W. Stone, The waters under the Earth [Bull. Penn. Dept. Int. Affairs, v. 8, No. 11, pp. 3-9, and No. 12, pp. 20-26, 1940].

Antioch College,
Yellow Springs, Ohio

REPORTS, PERMANENT RESEARCH-COMMITTEES, SECTION OF HYDROLOGY

NATIONAL ACADEMY - RESEARCH COUNCIL BUILDING
THIRD SESSION, 9:00 A.M., MAY 2, 1941

ANNUAL REPORT OF THE COMMITTEE ON SNOW, 1940-41

J. E. Church, Chairman
(Presented in abstract by Phil E. Church)

Personnel

The confusion of war and its requirements have deprived the Committee of its Vice-Chairman, Richard C. Farrow of Canada, who has gone overseas as Staff Officer, and its Secretary Carl Elges, who is a Lieutenant Colonel in active duty with the National Guard. Robert G. Stone, in in charge of bibliography, has been assigned temporarily by Blue Hill Observatory to New York University in meteorology. The unusual lack of reports from most of the members of the Committee indicates the temporary distraction of the times. However, Captain Alden K. Sibley, Assistant Engineer on the St. Lawrence Waterways Project with experience in flood-control in the arid West, has accepted service on the Committee and has been assigned to Water Supplies.

Progress

The progress during the year represents expansion in organization and concentration in research. The Eastern Snow Conference was organized at Harvard University, September 16, 1941, and the Great Lakes or North Central States Snow Conference at Detroit, December 12, 1941.

A Research-Committee was appointed by the former under the chairmanship of Gail A. Hathaway, Office of Chief of Engineers, United States Army, Washington, D. C. A Policy and Research-Committee was likewise appointed by the Western Interstate Snow-Survey Conference at Sacramento with the Chairman of the Committee on Snow as its Chairman.

Correspondence has already begun regarding a national union of the three conferences. The Chairman of the Committee on Snow has suggested that mutual consultation be initiated and maintained by the Chairmen of the Executive Committees of the three Conferences for the selection and apportionment of research-projects on the basis of regional fitness or need. It is hoped that close affiliation will be arranged with the American Geophysical Union as has been done by the older Conference in the West.

Evidence of expansion of interest into broader fields is found in the substitution of the title Snow for Snow-Survey in the newer Conferences. This indicates greater emphasis upon the general science of snow and ice which has followed in the train of winter sports and transportation by airplane and highways.

But even as the field is broadening the narrower name is acquiring permanence in the recently invented term niphometrology (snow-measuring). However, movements grow despite restricting names. But I fear that the heroics of the pioneer snow-survey days now becoming folk-lore will disappear with the parent Anglo-Saxon name, unless perchance the serious mishaps of the past season crown the new name with sinister meaning.

A broader technical name covering all phases of snow and ice has been urged by Dr. Antoni B. Dobrowolski of Poland. This is cryology (cold-science) that seems to be gaining currency despite initial resistance.

The season and snow-cover

The snow-picture this year is a composite one from very good to critically short.

The winter has been mild from Newfoundland to Oregon, and the low-level snow melted as it fell. But the high-level and high-latitude snow has been unaffected by temperature.

In Newfoundland and New England the snow-cover is normal. No frost is in the forest-floor. Floods are unlikely.

But in the West the snow-cover increases from a scant 60 per cent of normal in British Columbia and Montana to 130 per cent in southern California and Arizona. Interminable rains have changed sunny California into soggy California, but the Sun will shine again.

The following excerpts from reports paint a very vivid picture of deficiency and excess on the Western coast:

State of Washington (PHIL E. CHURCH)

"Lack of snow and rain combined with high temperatures and much sunshine in February and March left the ground, up to about 4,000 feet altitude, without appreciable snow as early as April 1. Higher up there was comparatively little snow, too; for example, Mt. Rainier (at Paradise Inn) had only 66 inches in contrast to a normal of 184 inches on April 1. The lack of a dense, thick snow-cover allowed its early removal. The only hope is for protracted spring rains to correct or alleviate the lack of water.

"Perhaps as serious as the low irrigation-supply is the impending extended forest-fire season. With the snow-cover gone a full two months earlier (above 3,000 feet in the mountains), the fire-season will be that much earlier, longer, and more severe. Again this will depend on spring and rains. The long dry spell in February and March indicated what may be expected, for on March 15 no less than 82 fires were reported burning in Washington alone, most of them west of the Cascades. None were serious, however.

"It was a poor season for snow-sports. No important impervious ice-crusts formed early this season; hence, there was almost a total absence of avalanches."

Southern California, Owens Basin (GEORGE A. LEWIS)

"We are in for another big water-year. Our calculated basin-percentages of normal are 132.3, 201.9, 149.0, and 166.0. Our Watershed as a whole is our second largest year of survey-record.

"I see by Dean Clyde's forecast that Utah did not fare so well and this seems in accord with other years when the major storms came from the southwest rather than from the northwest. Our storms were the same that caused such heavy precipitation in the Los Angeles Area and our snowpack reflects the diminishing strength of the storms as they moved northward.

"One peculiarity of our last disturbance was that the Inyos, which ordinarily receive only scant precipitation after the storms have unloaded on the Sierras, received greater precipitation than the Sierras.

"We are expecting to start storage in our Long Valley Reservoir within a few days. Quite fortunate that we have a new reservoir to fill in such a long water-year."

W. G. HOYT reports that the water-table in southern California is rising in response to the past and present rainfall-seasons.

Regional reports

The less spectacular but more essential facts of snow and runoff are reserved for the following regional reports.

Newfoundland (ERIC HINTON)

"The snow-survey of the Deer Lake Hydro-Electric Power Development was conducted in the same manner as last year. The main body of Grand Lake was again free of ice, thus permitting transportation of the party by one of the small Diesel tugs. This is the fourth winter, since 1926, that this favorable condition has obtained. A dog-team was used to transport the party over Sandy Lake. The whole survey was expeditiously conducted during very favorable weather. The snow-blanket is near the average, and is considerably greater than in 1940.

"The current winter has been mild and somewhat similar to the winter of 1932. A similar long flood-period of moderately intense runoff is therefore expected. While it is anticipated that the flood will commence between April 1 and 15, it is unsafe to operate the Power Plant upon this basis. For we have no data to substantiate this supposition and, therefore, must assume that the flood will commence at the latest experienced date, namely, May 1.

"Moreover, the estimated maximum Grand Lake water-level is elevation 375.5. Since this water-level is 2.1 feet below the maximum that Grand Lake can contain, only an abnormally high precipitation during the flood-interval could produce spilling.

"It is therefore apparent that operating policy should be such as to conserve water to the fullest possible extent until the flood begins. This involves continuing, for the present, operation of the Power Station at minimum load consistent with full production at the Mill, with all coal-boilers operating at full capacity."

New England (PAUL L. BEAN)

"We are continuing the work with the same scope, but suffering from lack of experience in our force.

"The depth and water-content of the snow-cover is below average at the lower elevations and approaches the average in the mountains and hilly sections of Northern New England along the Canadian border. It is what is rated as a mild winter with little danger of flood at this date. Somewhat below the average water-supply in the storage-reservoirs is indicated as of this date. The deficiency, however, is not so great but that heavy precipitation in April, May, and June can eliminate this deficiency.

"The forest-floor in the storage-area on the Androscoggin Area is not frozen this year.

"Daily broadcasts are sent out to the winter-sports fans and cover most of the White Mountain Area. The growth of winter sports in this area continues at a rapid rate and is of real economic value to the area.

"Frost-studies are being carried forward this year by the Maine Water Utilities Association and valuable results are being obtained. Their studies are available to the public through the Journal of the Association.

"The Weather Bureau is giving extended service to the New England Area, the value of which is appreciated by all river engineers."

New Hampshire (HENRY I. BALDWIN)

"We had an unusual drought in February with very light snow-cover which made people fear a water-shortage, but since then a good covering of two or three feet of snow has developed over New England which seems likely to last late into the spring. Another interesting thing was that the ground in most places is not as much frozen as usual when the first permanent snow-cover came in November, so that the ground has been largely unfrozen all winter. We have continued weekly snow-depth measurements on about 40 stakes in and outside the forest and a summary of these will be made when the present season is over, or in about a month. Last year there was snow the first week in May at some stations."

New York (ARTHUR W. HARRINGTON)

"At week-end of March 22, mild temperatures and winds have reduced snow-cover greatly in the lower elevations. Snow was heavy, packed, granular. Open areas in lowlands are bare or have patches of ice and snow; while in woods is quite uniform."

Continental Divide (RALPH L. PARSHALL)

"The snow-cover improves from Montana and Wyoming to New Mexico and Arizona. In southern Colorado the outlook is the best in years. Although the North Platte Basin is only 86 per cent of last season, the Arkansas Basin is 68 per cent better than a year ago.

"The snow-cover over the Colorado River drainage above Grand Junction is about the same as a year ago, but the White River, the Gunnison, the Dolores are 23 to 64 per cent better. The San Juan is even 196 per cent greater. The Rio Grande shows 200 per cent improvement."

(Editorial note--MERRILL BERNARD writes on May 16: "Have just returned from Albuquerque where we have the makings of a real 'snow'-flood on our hands." A news note of May 20 reports that under the stimulus of spring rains Lake Mead at Boulder Dam has reached a maximum of 26,000,000 acre-feet in a total capacity of 32,359,274 acre-feet. Its previous high mark was 25,000,000 acre-feet on July 29, 1939.)

Arizona (RALPH L. PARSHALL)

"All major storages report all-time records. Not only are reservoir-supplies of 1941 ample but substantial amounts will be carried over in storage to 1942. Moreover, pumping for irrigation can be curtailed which will mean that the evident rise of the ground-water due to heavy rains will help build up the underground storages. The soil-moisture condition throughout Arizona is generally good, the soil being saturated to depths greater than at any time in the last 25 years."

G. E. P. SMITH, Irrigation Engineer at the University of Arizona, writes: "My annual forecast was extremely optimistic this year. In fact, we reported that the farmers everywhere had carte blanche to irrigate all of their acreage."

Alberta (W. T. McFARLANE and O. H. HOOVER)

"In the Bow River Basin on the basis of 125 samples obtained at eight snow-survey courses the runoff at Banff should be 588,000 acre-feet for April to July or approximately 89 per cent of the long-term average.

"It should be borne in mind, however, that the runoff-percentage can be materially disturbed by torrential rains such as have happened heretofore during June and July in the Bow River Valley.

The Columbia River (S. H. FRAME and R. A. WORK)

"The depth of water with snow-cover in the upper Columbia varies with elevation throughout the River's length. The runoff at Golden is estimated to be 58 per cent of normal, at Revelstoke 55 per cent, and 52 per cent at Trail where the seasonal runoff should approximate 18,900,000 acre-feet. A 27-year normal has been obtained for the Columbia at Golden, Revelstoke, and Trail, for the period April 1 to August 31.

"The Columbia River Basin, except the areas lying south of Snake River in Idaho and Powder River in Oregon, will suffer water-shortages at least as severe as those experienced in 1907, unless rainfall this spring and summer is much greater than usual. During the past decade only two droughts--one of 1931 and the other of 1934--more severe than the one in prospect have occurred.

Coastal Area of British Columbia (S. H. FRAME)

"In the Coastal Area the weather during the past winter has been so mild that the snow-pack at lower elevations has completely disappeared, indicating a steady runoff from November to March and thus accounting for fairly full reservoirs. The snow at higher elevations, although of considerable depth, is less than normal, even being less than that of last year.

"In the mountains in the vicinity of Vancouver the depth of water in the snow-cover is about 28 per cent of normal up to elevation 4,000 feet. Above this it might be as much as 50 per cent of normal, although from a more than usually restricted area.

"On the Powell River Watershed conditions are similar. The depth of water in the snow-cover is 56 per cent of normal, this being ascertained from the average water-content of four courses. There are large areas of high elevation on this Watershed. The mild winter would tend to lessen the snow-pack at the higher elevations, say from 3,500 feet to 5,000 feet, although one course at elevation 3,100 feet gives the depth of water in the snow-cover as 74 per cent of normal. Above 5,000 feet the area becomes restricted and at this height the exposed slopes add very little to runoff owing to evaporation.

"Above average spring and summer rainfall will be required to assure an adequate water-supply for the season."

Washington (PHIL E. CHURCH)

"The amount of snow that fell this winter was considerably less than that of the previous winter; both were considerably below average. Not only was there less snow, but also there was less rain. However, the season during which the ground was covered was about the same as last.

"Much of December and most of February and March were without any snowfall. Only during November and January was the total fall about normal. This latter could have effectively stored some liquid precipitation had there been any. The lack of a dense, thick snow-cover allowed its early removal.

"The above condition is not a healthy one for Washington for it means low reservoirs with possible shortage of water for domestic and irrigation-purposes, a longer forest-fire season, and a greater consumption of fuel at booster power-stations. Though some reservoirs are full, many others are not. While most cities report an adequate supply for domestic consumption, these places usually rely on the natural flow of the mountain streams feeding the Reservoir until early summer. On the date of writing this report (April 1) many of these streams had dwindled to a flow about equal to the consumption. It is, therefore, quite likely that water-reserves will be drawn upon a full two months earlier than usual, unless rain is well above average this spring and continues later into the dry season.

"Seattle apparently has sufficient water for domestic purposes, but power-companies will need to supplement a greater fraction of their electrical output this summer by steam-power. Everett, Tacoma, and Bellingham all report adequate drinking and domestic supplies.

"If the present trend of subnormal precipitation continues, irrigation-storage will be inadequate. More water will be required because of the necessity of early irrigation. The outlook at present is a bare sufficiency for early season irrigation, but little or none for late watering. The only hope is for protracted spring rains to correct or alleviate the lack of water.

"It was a poor season for snow-sports. An index of the unfavorable season for skiing is to be seen by a comparison of the number of cars (counted by the State Patrol) at various popular skiing-places. During the past four winters at Snoqualmie Summit there were 15,000 (1937-38), 17,000 (1938-39), 9,000 (1939-40) and 12,000 (1940-41) cars. Though this seems to indicate better skiing this past winter than 1939-40, it must be remembered that beginning skiers go to the Summit, especially on clear days. Mt. Baker, the snowiest place in the State this winter, had but 4,000 cars compared to less than 3,000 the previous winter. Advanced skiers frequent Mt. Baker. The Milwaukee Railroad, which ran 37 snow-trains between January 6 and March 23 to the Ski Bowl in the 1939-40 season, ran but 32 trains between January 4 and March 9 this year.

"No important impervious ice-crusts formed early this season; hence, there was almost a total absence of avalanches. Again this winter, as also during 1939-40, the highways to Paradise Inn and over Stevens Pass were kept open."

Oregon (J. H. RYAN and R. A. WORK)

"October precipitation in Oregon was unusually heavy in every part of the State except the southwestern section west of the Cascades, varying from 116 to 242 per cent of normal.

"November, December, and January were very mild. February was unusually warm and dry. Some melting occurred during March.

"Soils on most watersheds, as well as in farmlands, were well wetted by heavy fall and winter rains. However, irrigation-supplies from unregulated stream-flow, and reservoired supplies will be critically short in some sections though fully ample in others.

"All of the area west of the Cascades has a light snow-pack and the fruit-growing sections of southwestern Oregon are faced with a very serious deficiency. At the present time storage in the reservoirs there is much below normal.

"The growing season is some three to four weeks advanced, however, and this will partially offset the deficiency in water available for irrigation of farm-crops. Heavy rains in May and June will be necessary to produce normal crops in the drier areas of the State."

The present and immediate field

Through the fortunate conference-plan snow-surveying has retained enthusiasm and plasticity. It has also acquired broad background and support.

This is best evidenced by the following statistics provided by the Division of Irrigation of the United States Soil Conservation Service, and the United States Weather Bureau. The Federal-State Cooperative Snow-Survey system led by the former now has 753 snow-courses with a total of 14,295 snow-sampling places. Backgrounding this is a network of mountain snowfall-stations spread by the latter over the Mountain States. The average elevation of 92 stations is 7,643 feet. Five stations are above 10,000 feet. The immediate program comprises 6,000 non-recording and 2,500 recording precipitation-stations. The catch of all gages, as of all snow-surveys, is determined by weight.

The preponderance of non-recording gages is due to the fact that where snow-cover prevails the intensity of precipitation has little or no effect on final melting and runoff and only the total need be known. However, where the snow melts early and spring and summer rainfall have a considerable effect on runoff, recording gages should be substituted for the others.

In any case all key-stations unless under constant supervision should be equipped with recording gages to provide a detailed background of the accumulation of the snow.

Supplementing precipitation-measurements are monthly reports on stream-flow data at selected stations throughout the country provided by the United States Geological Survey. This makes it possible to obtain early comparison between snow-cover or precipitation and stream-flow.

The value of this union of effort is cogently presented in the following letter from MERRILL BERNARD, Supervising Hydrologist and Service Coordinator of the Weather Bureau:

"If we could somehow get onto the common basis of understanding that adequate forecasting can never rest solely on either the snow-course or snow-gage, the way would be smoothed for a closer coordination of all interests. We here are firmly convinced that the water in the snow is only one of a number of important factors which can in practical degree be observed and evaluated. Also, that we should more positively express our anticipation of the future demand for forecasts having in them the quantitative elements of delivered volumes of water and approximate dates of arrival, that is, the forecast of a hydrograph. This, of course, to supplement the estimate of seasonal yield which we all agree is so important to planning. These thoughts are not new and I know I am voicing your own views, and those of others. In my opinion, we shall begin to make progress when the snow-surveyor demands precipitation-gages at key snow-courses, thermographs at selected stations, index discharge-stations for key-tributaries, master-stations to measure radiation, evaporation, and antecedent ground-surface conditions--all unfortunately demanding time and money.

"You will be interested to know that the Lakes Region Snow Conference was successfully organized at Detroit on December 12, 1940. We must plan on a National Convention some day."

Snow-surveying has entered two new fields quite naturally, namely, wildlife refuges and highways. In the former, snow-surveys are conducted cooperatively by the management of the United States Fish and Wildlife Service to determine winter snow-conditions and summer water-supplies. Regular surveys are now in operation in the Sheldon National Antelope Refuge and the Ruby Lake National Wildlife Refuge in Nevada.

In the Hawaiian Islands a plan is ripening to conduct snow-surveys on Mount Mauna Loa (elevation 13,680 feet) to determine the evolution of high-mountain snows in the tropics. This work would be conducted by Park Ranger CHARLES W. MILLER under the patronage of the United States Park Service and Division of Irrigation.

Of similar nature but with direct practical application is a request through Francisco Gomez-Perez, Civil Engineer, Mexico City, for a bibliography and general information on snow-surveys to determine the volume of runoff that may be expected from melting snows and ice. The immediate purpose is the use of water derived from the snow of Popocatepetl and Ixtaccihuatl, the two snow-covered volcanoes located in the central part of Mexico.

The relationship of snow-surveying to highway clearance is more novel but in reality is fully as intimate. In Washington State, the variant meteorological conditions that prevail on either side of the Cascades have created types of snow that require diverse handling for economic removal. Snow-sampling can quickly provide an analysis of the snow along the routes to be opened.

In California the Director of Highways requested a snow-survey by the Division of Water Resources to determine the weight and cubical contents of snow that must be removed to open the highway across the Sierra south of Lake Tahoe. A snow-survey showed that it would be necessary to move 163,000 cubic yards of snow weighing about 34,000 tons to open the 11-mile stretch involved, or approximately 400 pounds per cubic yard.

A similar method was suggested in the early days of snow-surveying as a means of determining the load of snow carried by the snow-sheds of the Southern Pacific Railway or other roofs when the snowfall had been abnormally heavy. However, if a building is completely buried in snow, the apparent weight on the roof would be misleading because of snow-cohesion that tends to form a bridge above the roof.

This picture assumes far vistas in the thoughts of PAUL L. BEAN, leading exponent of the quantitative snow-survey method in New England, who writes:

"It is highly desirable that the snow-surveys may be extended to adequately cover the whole country and Canada. The facts obtained are vital and their use of value along lines of endeavor which I never dreamed of. Surely some organization shall be set up to perpetuate the work and give it the driving force and publicity which it surely merits. The work must also keep pace with the rapid advance in meteorology."

Standing out like a monument among plans past and present for the regulation of stream-flow is Lake Mead with a capacity of nearly twice that of any other man-made lake. The upper 9,500,000 acre-feet of total storage capacity of 32,359,274 acre-feet is reserved for flood-control. "All of this storage-space can be made available at the beginning of each year's flood-season if snow-surveys and other hydrologic data indicate that it is needed.

"The present demand for irrigation and power is about 8,000,000 acre-feet per year. Even if the Colorado River should dry up entirely for a whole year or more, farms dependent upon waters of the lower Colorado for irrigation would not suffer and the huge generators of the Boulder Dam Power Plant could continue to supply power to the Los Angeles metropolitan area and the Southwest."--[Reclamation Era, September, 1940.]

On May 27 the storage of Lake Mead passed 27,500,000 acre-feet and the total capacity will be reached by late June.

The flood-waters of the Colorado River have attained the greatest volume since Boulder Dam was completed in 1936. S. O. HARPER, Chief Engineer of the United States Bureau of Reclamation, stated that even the comparatively small amount of 28,000 cubic feet of water released from the Dam every second was causing damage in the vicinity of Needles on the lower Colorado.

The Grand Coulee Reservoir now nearing completion has a storage-capacity of only 9,517,000 acre-feet although the total annual runoff of the Columbia at this point is 71,400,000 acre-feet or six times that of the Colorado at Boulder Dam.

Obviously Grand Coulee Dam is a regulator of low stream-flow rather than a total reservoir. Indeed the Columbia Basin has an excess of water for downstream-lands whereas the Colorado Basin is the reverse. Fortunately the large storage on the latter tends to equalize the discrepancy.

Special snow-surveys for forecasting underground water-supplies have been organized on the Charleston Mountains, southern Nevada, where artesian wells provide the entire water-supply of Las Vegas Valley. The rise in the ground-water level in southern California and Arizona during the past season of heavy precipitation indicates the immediate relationship between the two. Can a quantitative relationship be readily established? The snow-cover on Charleston Mountains of 2-1/2 times normal should provide a high point for a graph. However, the lowest point in the precipitation on the Charleston Mountains in 30 years, which occurred year before last, has not shown yet in the static of the valley-wells. HUGH A. SHAMBERGER, Nevada Deputy State Engineer, doubts very much that the effect of this season's heavy snow will be seen before 1942.

The Pahrump Valley in Nevada has several artesian wells, the largest one flowing 7.7 second-feet. The Steptoe and Big Smoky Valleys in this State are potential centers of pumping if economically justified.

Utah has already suggested the application of the general snow-surveys to forecasting both surface and subsurface water-supplies.

The best evidence of sturdy and permanent growth of snow-surveying is the eagerness of the public for forecasts of the season's flow. The following request from Douglas-Ormsby Counties, Nevada, is typical:

"Owing to the lack of adequate storage on the upper region of the Carson Rivers Mr. Krummes is attempting with considerable success to forecast from the seasonal percentage of the snow-cover the date at which the flow of the East Carson will drop below 200 second-feet [Trans. A. G. U., Part I, pp. 205-207, 1941]. The discordant factor is naturally the temperature, which may accelerate or retard the date. In 1939 the forecast was five days too early, in 1940 it was ten days late."

The routine nature of the forecasts appears in the label used by the Federal-State Cooperative Snow Surveys, namely:

FINAL
1941 WATER-SUPPLY FORECAST

Research

Floods--Research during the past year has centered around the question of the effect of snow in producing maximum floods, for it was feared that the heavy snow-cover in the mountains of the Pacific Coast might be a potential threat of impending disaster.

The conclusion that the deeper the snow, the smaller will be the flood from it has been accepted by WALTER J. PARSONS, JR., Army Engineers Office, Sacramento, California, as follows:

"The thick, winter snow-pack of the Sierra Nevada and Cascades, the natural storage-reservoir that supplies the vital irrigation-water to such a large part of western agriculture, also tends to mitigate the danger of flood on streams draining these mountains. The great storms that produce floods on these streams occur only during the winter season when a large portion of the drainage-area of these streams is covered by a thick, absorbent blanket of snow that catches the storm-rainfall and releases it at a very slow rate during the latter part of the storm-period or holds it until the next summer. This storing action on the higher areas usually over-balances the contribution from melted snow on the lower mountain slopes where the snow-pack is too shallow to persist throughout the storm-period. Flood-experience on these streams indicates that deficient snow-pack tends to increase the flood-hazard."

The disastrous floods in the Appalachians and particularly in the Susquehanna Basin have led CARROLL F. MERRIAM, Acting Chairman of the Research-Committee of the Eastern Snow-Conference, to institute a cooperative investigation of the critical density and temperature at which snow may suddenly release its water. His enthusiasm and energy have already made this project a major campaign.

Snow-melt and runoff--The general subject of the physics of snow and particularly its melting is receiving wide attention as shown by the following reports: Relation of soil-moisture and antecedent rainfall to runoff and runoff-prediction, by Dr. Robert E. Horton; The melting of snow computed by the energy-equation, by Robert E. Kennedy; A rational program of snow-melt forecasting, by Merrill Bernard; A new technique for the determination of heat necessary to melt snow, by Merrill Bernard and W. T. Wilson; An outline of the thermodynamics of snow-melt, by W. T. Wilson; Analysis of high rates of snow-melting, by Phillip Light.

The hydraulic laboratory of the Pennsylvania Water and Power Company and the soils laboratories of the United States Park and Soil Conservation Services are becoming research-agencies in snow-studies.

In answer to a question by the Chairman regarding the effect of rate of flow on total runoff, LEROY K. SHERMAN has expressed the problem and conclusion as follows:

"I am not the author of the statement 'that the total runoff of water from rains is not affected by the rate of flow.' In commenting on this, I want to be constructive, because the statement by itself, without giving the conditions, is rather ambiguous.

"The total runoff from a storm is governed by the amount of rain which falls at a rate of intensity greater than the infiltration-rate or the infiltration-capacity of the soil. The slope of the ground which affects the rate of surface-runoff has slight effect on the volume of runoff. It is a principle of the unit-hydrograph that, for the same basin, a storm which produces one inch of effective rain or runoff will have a period of runoff of X hours. If the effective rainfall on this same basin, for a storm of the same duration, has two inches of effective rain, then the period of runoff will also be X hours, but the rates of runoff will be twice as great.

"As to temperature-effects on runoff, the loss of water during the runoff-period, excluding ground-water outflow or base-flow, is negligible.

"This does not mean that temperature has no effect on runoff. A hot, dry spell, especially with vegetal cover, dries out the ground. This greatly increases the initial soil-capacity. Therefore, when the initial soil-moisture is low, the runoff for the same storm will be appreciably less than for the rain upon a saturated soil.

"I hope the foregoing may have some bearing on your question."

As reported by R. W. TRULLINGER [Report Agric. Exp. Stations, 1939], the Missouri Station has determined that infiltration is not affected appreciably by slope or rainfall-intensity but varies inversely with the initial soil-moisture content: "A decrease in runoff-losses due to increased permeability resulting from fall and winter plowing has been shown by the Arkansas Station."

Snow-cover--The evolution of the snow-cover is being studied annually by Dr. PHIL E. CHURCH, whose program has been recommended to the Research Committee of the Western Interstate Snow-Survey Conference. The specific object is "to follow density-changes occurring to snow-cover to determine rate of change at various places in western United States."

Snow-density and cohesion has been made an active project by R. A. WORK of the Division of Irrigation. He writes: "In connection with the Crater Lake Experiment we have observed the build-up of ice on the ground under conditions as shown in Table 1.

Table 1

Date	Snow-depth	Range temp. in snow, °F	Soil-temp. 1-1/2 inches below surface, °F	Thickness ice on ground, inch	Remarks
Apr. 15	103.0	31.7-32.0	32.6	None	Runout of water from snow beginning
Apr. 28	83.0	31.8-32.0	32.3	0.25	Runout of water from snow underway
May 13	68.0	31.9-32.0	32.0	0.37-0.50[a]	

[a] With some parts of ground-surface not covered by ice.

"The ground was unfrozen under the snow on all of the above dates. The ice on ground on May 13 was porous, that is, water would pass through it. No doubt there is some simple explanation for this icing phenomenon but none occurs to me just now. I might add that this ice build-up on the ground has been previously observed by snow-surveyors in this State. I have observed it myself on several occasions; however, such ground-icing does not always occur. Have you a ready explanation for this phenomenon?

"We are intrigued with the results to date of the experiment. Among other things they have shown the need for an improved method on which we intend to write you in more detail later, perhaps when this year's results are in shape to permit your review and comments."

A part of the explanation may be the following. The soil at first was slightly above freezing since it was dry, but because of the infiltration of melt-water at 32° from the snow overhead the temperature of the wet soil was reduced to that of the water itself. It is not at all probable that there was cold deeper in the soil that came to the surface. Rather the warmth penetrates downward from the surface and upward from the depths.

The formation of the ice is possibly due to a fall in temperature that caused the water-soaked ice at the bottom to freeze temporarily and form a crust. Such crusts at the bottom of the snow are not unusual. In fact small residues of snow of even an inch rest upon an ice-crust that seems to have been produced by the capillary water from above. The readings show that the range of temperature in the snow itself was a bit below freezing. This may account for it. Were these freezing temperatures at the bottom of the snow?

Evaporation--In the dry climate and drought (now fortunately broken) in the Southwest, G. E. P. SMITH is interested particularly in the effects of sublimation. His letter was written while the worry was still keen:

"During the drouth years I have been trying to make forecasts of the spring water-supply and have publicized these forecasts this last spring and the year before quite extensively by radio and news stories.

"You probably know that in the spring of 1939 we had a record-breaking snowfall on the high portions of the Gila River Watershed--and yet the disappearance of the snow took place without increase in the runoff. I may add that the ground was not very wet after the snow had disappeared. It seems to me that the conditions must have been right for maximum loss by sublimation, and that perhaps 60 or 80 per cent of the total snow was lost in that way.

"I am considering a proposal to make some tests of the sublimation of snow on the high parts of the Watershed next February and March, and I have no doubt you can give me a great deal of help in planning such tests."

Frost in soils--The movement of frost in soils has become a special study in Wisconsin and New England. Its more immediate purpose is the forecasting of imminent freezing in municipal water-mains. "I am glad to know," writes PAUL E. BEAN, "that you are interested in the frost-question. Much work is being done along this line in this area and has been continued for a number of years past. Valuable and accurate information is now available in meeting the problems of frozen water-pipes. The general public have difficulty in understanding how one can tell a week ahead of the time when their service-pipe will be frozen at a given location. If you desire, I will be glad to forward such information as it becomes available."

Snow-precipitation measurement has continued at Blue Hill Observatory with two shielded gages of the Nipher type. Dr. CHARLES F. BROOKS, Director, writes that "the Fergusson weighing recording gage catches snowfall better with a shield on than without, but the snow after being caught is often whisked out by the wind, for the depth of the can is not much greater than its diameter. The only cure, so long as the design is what it is, seems to be a vertical baffle, say, two flat sheets of metal crossing at 90°, and extending from an inch below the top of the funnel down nearly to the bottom of the can. Such a 'snow-cross' has been found successful in Denmark, U.S.S.R., and Germany. It has not yet been tried here, however.

"On Mt. Washington there are now three precipitation (snow)gages, with Nipher shields without wire-screening, each exposed at five to six feet above the surface and with their orifices parallel to the slope. No special studies of the results have been made during the year.

"In the Antarctic a wind-shield of the Mt. Washington type has been used (loaned by Blue Hill Observatory to Meteorologist H. G. DORSEY, JR. of the Expedition)." The following report from him has just been received:

"As for results obtained with the shield I took for the snow-gage, I have told you that no precipitation ever fell or reached the surface there during our high winds and drift-storms, since these came with dry easterly gales somewhat warmed in their abrupt descent from 5,000-foot plateau. The precipitation came mainly with light northwesterly winds. There was considerable snow with moderate to fresh westerly winds, but never strong enough westerlies to produce high drift. The snow-gage was mounted with the shield so that the top of gage was about six feet above the snow at its base, and was above all drift during precipitation. I assumed that this shielded gage would give the best measure of all precipitation, and having only two cans, unfortunately perhaps, made no comparison with an unshielded gage. Since most precipitation fell with light winds, I feel confident that this first precipitation-record from that part of Antarctica will be a good measure for that season. Also have fine 11 months snow-stick record from middle of unobstructed snow-plain nearby." [See Addendum, p. 979, for further discussion by Dr. Dorsey.]

The interpretation by Dr. CHARLES F. BROOKS, of the conditions noted by Mr. Dorsey at East Base is so excellent that it is included for the further understanding of Antarctic winds and precipitation:

"I think the East Base was so situated as to favor unusually low wind-velocities during precipitation. The mountains fairly close by on the east were so high as to make practically all the precipitation there orographic--when the wind was from sea and upslope. Winds from such directions would tend to make a bank of dead air before the mountains, over which the stronger winds from which the precipitation fell rode up the mountains. The coldness of the surface, favoring inversions of temperature, would also contribute to the tendency for dead air when winds were on-shore. Also, when there may have been cyclonic winds from easterly directions with precipitation from cyclonic action the cold air in the lee of the mountains would tend to remain in situ while the warmer precipitation-bearing winds aloft would slide over. The strong winds would be only the cold anticyclonic or fall winds favored by clear weather, and these would not carry precipitation--only drifting snow."

Rime- and glaze-measurement has been made intensively on Mount Washington this winter, and the results in terms of rate of formation per unit-passage of air, and density, have been broadcast thrice hourly and placed on the United States Weather Bureau teletype.

The riming program for 1940 is outlined by DAVID L. ARENBERG in Mount Washington Observatory News [Bull. 8, January, 1941]. The following factors are involved: Measurement of liquid water-content; measurement of drop-size distribution; the structure and physical properties of rime and ice; meteorological situations necessary for icing, development, and testing of de-icing equipment; measurement of wind-velocity and turbulance.

"The structure of rime varies from a simple one in which the air-spaces are all interconnected as in fragile rime to one where bubbles are distinct. The latter occurs when the time for the drops to freeze is sufficiently long for others to strike them and coalesce while still plastic.

"The transition-point is rather critical and important since it determines the strength of the rime and ease with which it can be dislodged. The readings confirmed past experience that the density rose with the wind-velocity, temperature, and liquid water."

The immediate research task of the Western Interstate Snow-Survey Conference, as outlined at the Sacramento Meeting by its keynote speaker, HAROLD CONKLING, Deputy State Engineer of California, is the analysis of the past ten or more years' data of the snow-surveys to determine persistent weaknesses and seek their causes. All data will be loaned freely to those who will undertake the task.

Regional problems are the search for key snow-survey stations in the upper Colorado and Arkansas Basins for purposes of more accurate forecast of stream-flow. Ultimately an investigation should be made of the Tennessee Basin to determine the value of snow, if any, under the extremes of scarcity that prevail there.

A distinct advance has been made in the study of forecast-problems in the Humboldt Basin, Nevada, by having a snow-survey March 1 and April 1 to determine the cycle of the snow-cover during the critical month of March. An unusual opportunity is thereby afforded to study the rate of melting of snow over wide areas.

The United States Forest Service is continuing its various research projects in snow and plans a further report before the Western Interstate Snow-Survey Conference.

A simple technique of preserving snowflakes for study has been developed by VINCENT SCHAEFER of the General Electric Research Laboratory [Science, March 6, 1941]. This is to encase the flake in a solution of formvar on a glass slide. The hardening of the solution preserves the specimen. The same method could be applied to snow-crystals in a snow-cover.

Maximum snow--The search for the deepest snow in the Pacific Northwest is approaching conclusion. The normal water-content of the snow cover at 8,400 feet on Mount Lassen is at least 92.2 inches. Until the present year only snow-depths had been measured on Mount Rainier and those only at 5,550 feet at Paradise Inn. At density of 47.6 per cent found April 1, 1940, on Mount Lassen, the normal water-content of the snow-cover (184 inches) on Mount Rainier should be 87.6 inches, slightly less therefore than on Mount Lassen.

Dr. PHIL E. CHURCH now reports that the rangers in Mount Rainier National Park consider that Edith Creek Basin (5,000 feet) has the most snow of any place they know in the immediate neighborhood of Paradise Inn. Edith Creek Basin is right at timber-line. Above timber-line drifting would prevent accurate measurement.

On April 1 of the present season, the snow-cover on Mount Lassen was 287.1 inches in depth with water-content of 134.5 inches (134 per cent of normal). On Mount Rainier, March 29, WILLIAM PRUITT, JR., Dr. Church's assistant, found a depth of 124 inches in Edith Creek Basin and only 71 inches at Paradise Inn. The snow-density at both places was between 49 and 50 per cent, indicating a water-content of approximately 62 and 35.5 inches, respectively. Unfortunately, however, the seasonal snow-cover was only 38.6 per cent of normal as compared with 134 per cent on Mount Lassen.

If the measurements are reduced to normal, the water-content of the snow-cover at Mount Lassen is 100 inches and at Edith Creek Basin on Mount Rainier 161 inches. Mr. Pruitt reports that there is little likelihood of deeper snow on Mount Rainier.

The probability of finding a region of maximum snowfall north of Mount Rainier is rendered doubtful by the fact that the season of maximum precipitation in Alaska is advanced one month as compared with Washington State, thus reducing the proportion of annual precipitation that falls in the form of snow.

The final decision must depend upon high-level snow-surveys on mountains, such as Mount Fairweather, of the South Alaska Area.

Suggested projects--Other problems that have possibilities are: (1) The proportionate influence of snow and rain on the runoff of so-called rain-fed streams, like the Willamette River, Oregon; (2) further analysis of the destructive rain-flood of September, 1939, on the lower Colorado described by L. J. FOSTER [Eng. News-Record, December 7, 1939] and the recent snow flood on the Rio Grande reported by MERRILL BERNARD; (3) the relation between the flow of the White River at the base of Mount Hood and the seasonal diminution of the glacier and residual snow at its source.

H. P. BARSS, United States Office of Agricultural Experiment Stations, suggests that the search for a metal of low wetting and conduction-coefficient suitable to replace duralumin now used for snow-samplers be referred to national laboratories such as that of the E. I. du Pont de Nemour Company.

The study of water-temperatures in connection with the formation of frazil in the Truckee River, California-Nevada, below the Boca Dam was begun the past winter by the Sierra Pacific Power Company but was quickly terminated by the sudden return of the temperature to normal.

Conservation

Professor JOSEPH KITTREDGE, JR., continues his study of the conserving effect of forests on snow, and presents the following summary for the report of the Committee on Snow:

"Analysis of a fragment of the records of the California Agricultural Experiment Station project on snow under the direction of J. Kittredge, indicates the relative importance of factors in the distribution of snow to leeward and north of a forest-margin. Measurements of the water-equivalent of new and old snow in the Stanislaus National Forest during 1936-37 and 1937-38, near Strawberry at an elevation of 5,200 feet, give evidence of the effect of a forest-border to windward on accumulation, evaporation, and melting. A large open area is bordered on the south by a mixed stand of pine and white fir 35 to 50 feet high. Snow-bearing winds are southerly. Ten snow-stations have been located in three rows at distances from 5 to 178 feet from the edge of the forest. For both seasons the average water-equivalents of the total new snow for all of the stations were nearly the same, so that the forest-border exerted no significant effect on the snowfall. For example, in 1936-37, the station only ten feet from the edge of the forest had a total snowfall of 22.5 inches, water-equivalent, while the station at 178 feet from the edge had 21.6 inches. The intervening stations varied only slightly within this range. In 1937-38 a similar comparison is from 30.3 inches to 33.9 inches.

"Although the forest had no significant influence on the accumulation of new snow, it was found that the effect of the forest-border on evaporation and melting was significant, as indicated by the differences in total water-equivalent of old snow. Measurements taken on three different dates in March and April in each season showed more snow near the trees than at greater distances. On March 4, 1937, the station ten feet from the trees had a water-equivalent of 19 inches, the station 58 feet away of 13 inches, and the station 178 feet away of 12 inches. In the same year on April 18, the respective water-equivalents were 21 inches, two inches, and one inch. On March 24, 1938 they were 31, 24, and 23 inches. From these data it is evident that as the distance from the forest increases up to 60 feet, the water-equivalent decreases. Consequently, because the snowfall is the same, it follows that evaporation and melting are more rapid farther from the edge of the forest, where more solar radiation reaches the snow. The effect extends from 1-1/2 to 2 times the height of the trees."

The method of conserving snow in open fields, initiated in Canada, has been further developed in North Dakota. The following details have been reported by R. W. TRULLINGER: "The value of snow-ridging to conserve moisture and decrease erosion has been demonstrated by the North Dakota Station. The use of snow-plows and crowders to build up ridges 18 inches high from a five-inch snowfall resulted in holding much snow on fields, while similar areas not ridged were blown clear of snow after a thaw and freeze. With snowfall of less than five inches a second ridging is necessary. The best results are obtained by ridging at a temperature high enough so that the snow is damp. The ridges should not be more than eight feet apart and should be at right-angles to the prevailing wind. On rolling ground, they should be on contours. The best equipment for this purpose included a push-plow driven by a large tractor capable of drawing two pull plows offset back of the draw-bar.

The relation of scant snow-cover to increase in forest-fires in Washington has already been referred to by Dr. Phil E. Church [p. 956]. A close relationship between fuel-moisture and air-humidity has been found by WALTER E. BROWN at the Caroline A. Fox Research and Demonstration Forest, Hillsboro, New Hampshire, who reports as follows:

"Fuel-moisture was determined by weighing thin basswood slats, which were exposed horizontally on wire supports about six inches above ground beneath a cover of pine and hardwood-slash simulating conditions on blow-down areas. These fuel-moisture sticks, developed by the United States Forest Service, have been found to absorb and give up moisture, closely paralleling the behavior of forest-slash and litter in this respect. The sticks were weighed on a special scale reading directly in moisture-percentage.

"It will be noted that high average humidities in the summer months may be associated with low fuel-moistures due to a more rapid drying gradient during long days, but in general the two values follow each other."

The relative value of watersheds particularly for their financial income is being determined by W. W. McLAUGHLIN, Chief of the Division of Irrigation, United States Soil Conservation Service. This income may be variously provided as in timber, grazing, water for agriculture and power, recreation summer and winter, mining.

Dr. HENRY I. BALDWIN stresses the same point: "Forests must be used for man's commerce and enjoyment. They are not a luxury to be supported; they are the means of support."

The parks or emotional side of man's environment are assumed under recreation and enjoyment. These may or may not have money value but add to the spiritual strength of a people.

The possible effect of long periods of drought in the survival of tree species that are sensitive to water is commented on as follows by H. T. GISBORNE, specialist in Forest Protection, United States Forest Service, Missoula, Montana:

"Your suggestion concerning the factors or features of the precipitation which are critical to tree-growth is a new idea to me and certainly is part of the attack that must be made by someone, sometime. And the sooner the better. C. A. WELLNER on our station staff knows much about the water-requirements of various tree species. He is also a rabid snow-surveyor and has made practically all the snow-course measurements on Mt. Stuart for the last five years, as well as supervising the measurements for two courses on our Deception Creek Experimental Forest."

Polar regions

The interest in the Polar regions oscillates between Antarctica and Greenland. The explorations by Lincoln Ellsworth and the recent expedition by the United States under the leadership of Admiral Richard E. Byrd indicate the continental character of Antarctica. The scientific results of the latter, however, except the geographical have not yet been publicized.

Unfortunately the snow-cruiser was found to have a gear-ratio unsuited to the Antarctic and was not used. Thus its ability to traverse soft snow and crevasses was not determined.

Evidence of retreating ice in Graham or Palmer Land has been presented under the title "Relic glacial forms on the western seaboard of Graham Land" [Geog. J., August, 1940] by Rev. W. L. S. FLEMING. With the collaboration of COLIN BERTRAM and BRIAN ROBERTS, he has also presented a richly illustrated narrative of the British Graham Land Expedition of 1934-1937 led by John Rymill entitled "Three Antarctic years" [Can. Geog. J., January, 1941].

Icebergs and submarines have focused attention on the coast of Greenland.

At the meeting of the International Commission of Snow and Glaciers at Washington, D. C., in September, 1939, the drift of icebergs into the North Atlantic and protective measures against them was discussed by Commander EDWARD H. SMITH of the International Ice Patrol. Since these icebergs originate in the Greenland fiords and the number varies greatly from season to season, the Ice Patrol authorized, beginning with the summer of 1940, a three-year experimental census of the icebergs and their autumn location along the drift-route from northeast Greenland to Labrador.

A cruise was made by Commander Smith to Angmagssalik on the southeast coast last summer and thence along the west coast to Davis Strait and Baffin Bay [pp. 788-792]. On the west coast in a total cruise of 3,360 miles, 3,289 icebergs were counted. It was estimated that there was a total of 6,000 bergs in Baffin Bay and Davis Strait.

Six important sources of icebergs were found with settlements nearby from which a count of passing bergs could easily be made. An airplane cruise in the autumn could disclose the location of iceberg groups in position to enter the sea-lanes the coming spring.

Two samples of glacier-ice were brought for the use of Dr. MAX DEMOREST for his researches on the physics of glacier-ice being conducted at Yale University.

The winter just past in Greenland was mild although the cold in Denmark was unusually severe. Open water was reported in the Northwest Passage in 1940.

The menace of submarine and airplane against shipping in the North Atlantic is increased by the great number of fiords in southern Greenland which provide easily fortified and mined focal points of ambush. The Reports of the Greenland Expeditions of the University of Michigan conducted by Dr. WILLIAM H. HOBBS are providing an abundance of detailed information on meteorology and physiography now eagerly sought.

Transport

Transport in winter for commerce, pleasure, and war coupled with increasing accidents to skiers and snow-surveyors has inevitably forced consideration of safety measures.

Safety--Two years or more ago the leader of a snow-survey party of three in Utah stepped on soft, dry snow overlying a rock-ledge or hard crust and caused it to avalanche with him. This past winter another snow-survey party of two in Nevada was carried down by soft, wet snow that seemed firmer than any traversed during the previous three seasons. The second member of this party was carried into a tree where the snow was broken into air-pockets and after regaining consciousness an hour later, though his face was badly broken, managed to extricate himself but too late to save his companion, the tip of whose ski still protruded from the snow. A detour around this avalanche-area by descending to the depth of the valley was available with a shelter-cabin just beyond but the summer route along the contour seemed easier. Since this was the first day of a four-day trip and no alarm at home would have been felt until the period was fully up, the member who escaped immediate death would have perished had he not been able to stagger home. Miraculously one of each pair of ski was recovered on which to escape.

Avalanches this spring on Mount Washington and Mount Katahdin caught snow-mountaineers but without serious injury.

Fortunately the Swiss Snow and Avalanche Commission has been making an intensive study of snow-texture and avalanche-conditions in the Alps, particularly for its troops who are deployed upon the mountain slopes. Its film on snow and avalanches shown at the meeting of the International Commissions of Snow and Glaciers at Washington, D. C. in 1939, can be duplicated with English titles and narrative. Voluntary contributions by various organizations have already been started. The film should be available to all without cost except for transport and insurance.

Professor Dr. E. MEYER-PETER of Zurich has personally sent to the International Commission of Snow and Glaciers a copy of "Lawinen: die Gefahr für den Skifahrer" prepared by the Swiss Snow and Avalanche Commission and Parsenn Service, summarized later in this report.

A simpler handbook based on American conditions and experience has been proposed by Director S. B. DOTEN of the Nevada Agricultural Experiment Station. An analysis of snow-slide records and related climatological data has been prepared and published in the press by the United States Weather Bureau Office at Salt Lake City. A report to the Army is being prepared by Alexander Hildebrand based largely on Gerald Seligman's "Snow texture and ski-fields". From these efforts a usable book should emerge.

Added to the menace of avalanches are the minor injuries received in falls by skiers through the twisting of ankles and bones by the rigidly fastened ski, which act like a gigantic wrench. In the mid-winter snow-survey, when the snow was soft, a forest-ranger broke through crust, thus badly injuring his ankle. By the aid of his two companions he was taken three miles to a shelter-hut erected only two years previously for snow-surveyors. A toboggan was obtained but could not be dragged loaded through the soft snow by men on ski. After two weeks, when the snow had settled and the ankle grown stronger, the ranger traversed the 20 miles with sled-transportation. A snow-survey supervisor had a knee badly wrenched but had necessary assistance.

In addition to the instructions that should be provided by film and handbook, there should be precautions rigidly enforced. The following are suggested:

(1) A detour-route around and preferably above all known avalanche areas should be designated and sufficient shelter-cabins provided to avoid the resulting weariness of the detour.

(2) In areas under suspicion the party should spread out in order to place less weight on the snow and act as rescuers in case one is carried down.

(3) Preferably three rather than two should constitute a party to provide a standby for the injured and a messenger for aid.

(4) A radio should be kept at shelter-cabins for emergency calls and, if remote, for the reporting of snow-measurements.

(5) A toboggan and web snowshoes should be available within reasonable distance. The web shoes will give better traction in soft snow.

(6) A snow motorsled capable of steady progress in unconsolidated snow should be kept at a central station in the principal snow-areas for use in carrying snow-parties far into the mountains on routine duty or for purposes of rescue.

(7) In the steeper mountains a forecast-service of snow-texture and avalanche-possibility should be developed as a part of the forecast of skiing conditions.

The days of adventure should now give way to safety. Can not a ski fastening be developed that will automatically release the foot in case of a spill? The snow-surveyor must obtain his measurements but with reasonable safety.

(Since the Report was written the following letter has been received from H. I. SNIDER, District Ranger, United States Forest Service, who was marooned by ski-accident in the American River Basin: "We are very much interested in your move to make snow-surveying more safe and I am able to state that there are on the market now two or three different safety-bindings, one of which is sold by Rossarrini's store at Truckee for $4.95 per pair. They have been used by the Truckee skiers this winter with very good success and I believe have not failed to kick out on a leg twist or when caught on some object. In regard to snow-motors for use in rescue parties, especially during the spring of the year, I have not much faith in the satisfactory performance under all snow-conditions by any type that I have seen yet unless it would be the double revolving spiro-drum type that JAMES McIVER, JR., of Truckee, California, has used several years in the past when he was carrying mail to Tahoe City. It will go most any place as long as it does not need to travel on powder-snow without a packed sub-surface. Usually during the spring months when snow-surveying is done, we would find a snow pack that would be ideal for its use as long as it would not become tangled up in too thick reproduction to prevent its passing through same. It strikes me that it would be a very good idea to have the availability of such outfits listed with snow-surveying organizations, so that they would know where same could be obtained in a needed emergency.")

The educational progress now under way is shown by the following letters from BESTOR ROBINSON First Vice-President and Chairman, Advisory Committee on Equipment and Technique, Winter Defense Committee, National Ski Association of America and Dr. CHARLES F. BROOKS, Director, Blue Hill Meteorological Observatory, Harvard University and President, Mount Washington Observatory:

"I am extremely interested in your letter of March 11 to Dr. Brooks with regard to the possibility of securing an avalanche film. I am sure that the cost could be repaid by a nominal rental fee to organizations showing it.

"Personally, I have been hammering away on the subject on another line: (a) By calling attention in official bulletins to avalanche-hazards and the necessity of clubs instructing their members in avalanche-technique; (b) by formulation of national ski-tests, one of which, the Ski Mountaineer's Test, will include an examination on the subject of avalanches and avalanche-hazards; (c) inclusion of the same test in the objective Army proficiency-tests for ski-troops; (d) attempting to get an appropriate text on the subject. The best thing that I know of is the publication by Seligman in the 1934 British Ski Year-Book, which reappeared in the general text of 'Snow-structure and ski-fields'. Do you know of any other material which could be utilized for this purpose?

"I am to see Arnold Lunn, Editor of the British Ski Year-Book, this weekend and will talk to him concerning consent to the use of this material."--B. R.

"I have written to the General Staff recommending that they procure a copy of the Swiss avalanche-film for instructional use in connection with the development of ski-troops. I will undoubtedly hear within a few days and will let you know.

"Alexander Hildebrand is preparing a memorandum for the Army on avalanches, relying of course largely on Seligman. I note in your letter to Mr. Show a reference to a booklet just received from the Swiss Avalanche Commission. Would it be possible for me to borrow this for a few days so that it could be utilized by Alexander Hildebrand in his splendid work? I presume the text is in German, but that is immaterial."--B. R.

"In the fall of 1939 the International Commission of Snow and Glaciers meeting in Washington, D. C., was shown a Swiss film on avalanches. Recently avalanches in the east, including this spring that one on Mt. Washington which injured Paul Gerhard and another on Katahdin, which buried one man but did not injure him, also a fatal avalanche in Nevada this spring, make it seem highly desirable that we obtain a copy of this film in the United States.

"Professor J. E. Church, Jr., President of the International Commission of Snow and Glaciers, at Reno, Nevada, suggests that his Commission be the depository for a copy of this film the cost of the film to be contributed by organizations and individuals, and the film to be available on loan simply for the cost of express to any organization or individual wishing to show it. I find on inquiry from Switzerland that at the present rates of exchange a copy of this film with English captions may be had for something less than $100. The actual figure checked on was $86. Our Mt. Washington Observatory will contribute $10 toward the cost of this film. I hope that your organization can match us with a similar amount. Professor Church is passing the hat around among western ski-groups, hydrological interests, and individuals, hoping to get at least half the cost of the film there. I shall make further efforts myself in the east. We hope very much to get enough money together by early this summer, to assure our having the film on hand by the beginning of the coming snow season."--C. F. B. in letter to R. M. Davis, Eastern Slopes Ski Club, North Conway, New Hampshire.

Ski-lift--"The world's longest and highest chair-lift in the world is nearing completion over the green-clad slopes of Mount Mansfield, popular New England winter sports-center. The lift will be in operation by the time Central Vermont Railway inaugurates the weekly ski-train, Ski Meister, from New York and Boston. The lift which will have a horizontal length of 6,330 feet and a vertical height of 2,030 feet, will be capable of handling 200 passengers per hour." --Official Bulletin, United States Travel Bureau.

Ski-lodges--Snow pleasure with comfort is being provided in many ski-areas. The picture in New Hampshire is typical:

"The opening of several new ski-lodges in New Hampshire has been pointed to by the State Planning and Development Commission as an indication of continued growth of the winter vacation business and the constant attention given to the comfort of skiers and other recreational visitors.

"A chalet-type hostelry is an interesting addition to the facilities of Franconia. A large house has been transformed into a pleasing replica of a Swiss chalet with a huge fireplace, bedroom balconies, and other typical Alpine features. Cannon Mountain skiers can run right into the chalet by way of Coppermine or Tucker Brook ski-trails.

"On a high hilltop in Sanbornton, not far from Laconia, is the Steele Hill Farm Inn, a newly remodeled farmhouse commanding a splendid view of mountains and lakes.

"At North Conway a new and attractive building, a chalet-type ski-barracks, has been erected on the site of the Sunset Inn main building which was destroyed by fire last June. This is part of the Eastern Slope Inn set-up.

"At Plymouth is Tobey's motor court with connected series of apartments, equipped for cooking, and one-car garages. Opened last summer, this is said to be the first establishment of the kind in this part of the country."--Travel News, United States Travel Bureau.

Snow-removal--As more briefly narrated before in this report, in the State of Washington--where diverse weather-conditions prevail as in the Cascades, the Columbia River Gorge, and the Continental Divide--the clearing of snow from the highways can be expedited by preliminary snow-sampling to determine the type of snow to be handled. The Department of Highways, State of Washington, is a pioneer in the work (Trans. Amer. Geophys. Union, Part III, pp. 932-935, 1940).

In California an 11-mile stretch of mountain highway was actually surveyed by the California Division of Water Resources to determine the feasibility of opening the route to winter traffic. The appended news item gives details:

"Approximately $48,148 would be the cost of keeping United States Highway No. 50 from Kyburz to Meyers, Eldorado County, open during the winter, it was learned from Sacramento today. The report of the cost was made by the Water Resources Division to the State Highway Commission.

"Businessmen and resort owners in the area have been clearing the snow blocking the highway by hand-power, but efforts were stopped by the last storm. A survey made by the Water Resources Division at the request of Frank W. Clark, Public Works Director, showed that it would be necessary to move 163,000 cubic yards of snow weighing about 34,000 tons (417 pounds per cubic yard) to open the 11-mile stretch between Twin Bridges and Myers.

"Additional equipment, including two rotary plows, push-plows, and light and heavy trucks, costing $44,000, would be necessary to keep the road clear, according to a report by the Public Works Department. Garage and housing facilities which would be necessitated by the purchase of equipment was estimated at $30,000.

"The cost of opening the road last spring was $5,071.53, as shown by a highway division report."

Snow-drainage--The Engineering News-Record (January 2, 1941) reports editorially that "snow-removal from our highways now receives a large portion of the maintenance money spent in many States. Windbreaks are erected to prevent drifting, but much snow falls on the highway surface where it becomes a serious hazard, as present-day drivers feel entitled to drive at a maximum speed-limit regardless of the condition of road. Plows push the snow off the traveled way, but in doing this compact and pile it in such places that the surface-drainage system of the road often fails to function; subsequent melting and freezing produce an extremely hazardous ice-film. These conditions frequently are aggravated on divided highways whose cross-sections are more diverse and drainage-systems more complex than the single-lane road. Consequently, it is encouraging to note that surface-drainage designs of some divided highways, as described in this issue, now are based on providing space for snow-storage. Road surfaces are crowned and ditches are so designed as to dispose of snow-water without its flowing on the highway surface. Experience with these designs should lead to improvements that can be incorporated in future divided roads."

Snow-fences--When the snow is too deep to be controlled readily, railways are protected against blockade by snow-sheds, which however are usually unpleasant because they obstruct both light and view. On the Canadian Pacific Railway snow-sheds are sometimes of concrete and where feasible detours are built around them for summer use.

If the snow can be controlled, snow-fences are preferred even when high and complicated in pattern to meet varying conditions of wind and slope. In the mountains of Norway the snow-fences are unusually high and in the uplands of Sweden, where the wind over wide areas is unobstructed by forests, the height of the fences indicates the cumulative effect of wind and drifting snow. Only in the pine- and fir-forests do snow-fences become low or disappear.

The Japanese scientists have undertaken efficiency experiments by means of models of fences in a wind tunnel. Fine powder is used in place of snow.

The following observations are reported by MASAWO KURODA and KOREO KINOSITA [Bull. Inst. Phys. Chem. Res., v. 19, p. 8, August, 1940]:

"The wind blows in counterwards behind the fences. This drifts snow to the fence and makes the snow-layer shallow behind the fence to the distance of approximately several times its height.

"If there is a secondary fence behind the main fence at the distance of about ten times the height of the latter, a calm zone can be gained between them to prevent a cut there from being buried by drifting snow.

"Experiments were also performed with triangular sections of different proportions. From them we derived some explanation of the formation of a snow-cornice."

De-icing plane-wings--The partial success previously attained in clearing airplane-wings of ice seems now to have been made complete by means of a simple invention by RUSSELL S. COLLEY, Kent, Ohio. He points out [Bull. Amer. Met. Soc., April, 1941] "that the inflatable shoes, which are attached to the leading edges of airplane-wings, are effective where they are alternately inflated and deflated. However, it is necessary to have non-extensible strips to hold the edges of the shoes. Since only a small edge, or a sudden change in contour, is enough to cause ice to accumulate, it may form on these strips. The invention provides for an additional inflatable strip to go over the edges of the shoe. The front of the extra strip moves with the large one while the back of it is attached smoothly to the wing, and no ice may form."

Clearing snow from airport-runways--A snow-remover has been designed by JOHN B. SWEENEY, Assistant Chief Engineer of the Allegheny County Bureau of Maintenance, that "virtually burns away the snow" at the local airport. As described by Engineering News-Record, "The novel equipment consists of a 7- by 10-foot wide box equipped with six burners fed by a mixture of crude oil and air from a 300-gallon tank-truck.

"On the first test the machine cleared a ten-foot wide path of three-inch snow, operating at a speed of six-miles per hour. A scraper attached to the front end of the steel box heating-chamber removes deep snow and at the rear a wiper blade spreads out the water from the melted snow, thus helping the heated pavement to evaporate the water. It is estimated that an emergencylanding area, 150 feet wide and long enough to permit planes to land and take off, could be cleared with the machine in an hour."

Snow-cohesion and snow-loads

The problem of snow-cohesion includes not only resistance to snow-sliding but to total weight of snow on roofs.

In the mountains where the snow-cover is extremely deep the snow-load is estimated far above the actual but in regions where the snow is relatively shallow it is too often ignored.

In the former instance a research project is contemplated by R. A. WORK of the United States Soil Conservation Service at Crater Lake, Oregon, in cooperation with the United States Park Service. It will doubtless be found that snow possesses far more cohesive and frictional quality than gravel or possibly finer soil over culverts.

Dead weight on roofs also is complex. Where thawing and freezing alternate, the roof-load instead of remaining equally distributed may be transferred to one portion of the building in sufficient quantity to break overhanging eaves or even entire sections. Thus snow-shoveling has become a winter profession where snow-loads manifestly exceed the supporting strength of the buildings.

In the case of burning buildings, snow-loads have constituted a hazard in Massachusetts according to the following note by Dr. C. F. BROOKS [Bull. Amer. Met. Soc., April, 1941]:

"Snow, weighing nine pounds per square foot, blanketed the roof of the Strand Theater in Brockton. The building caught fire. Firemen, fighting the blaze inside, were suddenly crushed by the unexpected fall of the roof; 14 were killed. They had not figured on the weight of the snow.

"More snow fell, making the weight 12 pounds per square foot. A junior high school in Lowell caught fire, March 11, 1941. The firemen overlooked the lesson of the Brockton fire three nights before. The main roof crashed in only half an hour after the fire was discovered. Fortunately, the three fire companies escaped without fatalities, though there was one fireman seriously injured."

In the West, where snow-loads are not over-heavy, roofs are planned to bear an extra load of 20 pounds per square foot. Could the supports have burned away sufficiently while firemen were still in the building or could the snow-loads have become concentrated? The latter does not seem probable.

Snow-sampling to determine loads on the railway snow-sheds of the West was a dream of the Chairman in pioneer days but the snow-sheds were usually built against possibility of snow overload. Snow-sampling might find a field on roofs not so sturdily constructed.

Snow and summer outings

The relation of the annual snowfall to the summer openings of the trails in the high mountains was a subject of study by ALEXANDER G. McADIE when Meteorologist of the United States Weather Bureau at San Francisco early in the century when the Sierra Club was young.

Now that mountaineering both winter and summer has grown to a national sport the problem has returned with gentle insistence. The Sierra Club's editorial merits quotation:

"The May's-end holidays bring the first of the season's outings--this year, as before, a mountain spring-time trip to Yosemite, when waterfalls are at their best. The high country trips will soon follow.

"To those who plan the outings there can often be more than beauty in the silvery torrents that plunge over Yosemite cliffs. There can be a sense of relief. Each acre-foot of water over the falls can mean just that much less snow to cover high passes and camp-sites. This year's concern about heavy snow-packs, however, has already been alleviated by the latest bulletin of California Cooperative Snow Surveys. Although it forecasts a summer stream-flow from the snowpack ranging from 139 per cent of normal on the Tuolumne to 197 per cent on the Kern, snow-conditions are much milder than in 1938, when even the mules seemed to enjoy the snow-enhanced alpine beauty of the High Sierra.

"Perhaps there will some day arise from Sierra Club ranks a member who can translate the volume of waterfalls and the snow-survey reports into exact dates of opening of Sierra passes and favorite camping areas. But until that expert steps forward it is at least reasonably safe to forecast a particularly beautiful summer, with plenty of spectacular snowfields on the peaks, ample water in the streams, wildflowers in the meadows, and a lot of bronzed, happy faces on the trails. Only the anglers need worry. High streams will mean more hiding space for trout."

In the case of the higher snows, the opening date of the trails will doubtless correspond with the percentage-of-normal of the snow. A comparison of years of normal snow-cover and Sierra Club experience should establish a normal date. On the lower levels temperature will be an accelerator or retarder of the date with departure from its normal.

Why not a forecast of summer pleasure as of winter skiing?

Indeed mountain climbing on ski in midwinter is competing with rock-climbing in summer. This is a source of intense satisfaction to the Chairman and would be to BOLTON COIT BROWN of Stanford, if he were living. Both began snow-outings at the turn of the century through fascination by the winter landscape.

The former with a companion, Allison, climbed Mount Rose (10,800 feet) in midwinter, 1894, and he and Mrs. Church spent their Christmas vacation in 1901 on the crest of the Carson Range and made the second winter ascent of Mount Rose. In early March, 1905, with G. F. Marsh as guide, he ascended Mount Whitney to 13,300 feet where new snow on the brow of the cliffs began to avalanche under foot.

This latter trip required eight days double sledging on the mountain and was made to galvanize Californians into the conviction that winter snow could do no harm. As a consequence of this trip, a weather observatory was immediately established on Mount Rose and prolonged winter trips have been made up Mount Rose and through the Tahoe Region every year since.

Pioneer of pioneers was JOHN MUIR, who accomplished an overnight winter trip up Mount Shasta (14,161 feet) and sought refuge from the storm over the fumaroles on the summit. And G. F. MARSH in 1906 emboldened by the trip of the previous year, made an early ascent of Mount Whitney in spring without companion. In early April, 1908, CHARLES H. LEE with two companions climbed to Kersearge Pass (12,000 feet) "with very little difficulty."

The titles in early numbers of the Sierra Club Bulletin indicate the zest of discovery: "A New Year Outing in the Sierra" [February 1903]; "Up from 'the Land of Little Rain' to the land of snows--Being the journal of a sledging trip up Mount Whitney in winter" [June 1909]; "Winter in the High Sierra" [June 1910]; "A midwinter trip through Nevada's Mountain Park" [June 1912]. Supplementing these is "The human side of snow: The saga of Mount Rose Observatory" [Sci. Mon., February, 1937].

The series of shelter-cabins a day's trek apart up King's River Canyon to the crest of the Sierra once dreamed of may be no longer necessary in these days of normal camping on the snow.

Equipment

Snow-sampler outfit--Severe test of the Mount Rose snow-sampler on Mount Rainier in heavy ice-crusts indicates that a sturdier construction of joints and spanner-wrenches is necessary. The duralumin metal also does not stand up well in the slots under heavy pressure on the driving wrench. Some teeth of the cutter also were broken by driving through four inches of ice. However, the penetration of the ice is an achievement rather than a failure, for the test of the sampler in the laboratory indicated its power to drive through only one and one-half inches of ice. At least temporary teeth can be filed in the cutter when the original teeth are broken.

For extremely deep and severe driving in snow the steel sampler, still used by Los Angeles, will be most dependable.

The latest model of the Chatillon and Sons iso-elastic spring-balance is winning the favor of snow-surveyors for its size, weight, range, and legibility, but requires minor adjustments.

A canvas carrying-case has been designed by PHILIP S. COWGILL and CARL ELGES for carrying the entire snow-sampling equipment in the field. It consists of a main case for the usual equipment and a supplemental case for additional sections of the sampler. The latter can be made a part of the main case or can be carried separately. [For details of balance and case see Trans. Amer. Geophys. Union, Part III, 1940, and Part I, 1941.]

Snow-motor sleds--Because of the tendency of the sled to skid and overturn on steep slopes and inability to travel without injury on dry ground, the spiral cylinder drive of the Tucker snow-motor sled [see Trans. Amer. Geophys. Union, Part III, 1940], has been changed to a caterpillar type (Fig. 1) providing greater speed in soft snow with less power.

The 'Sno-Motor' designed by the United States Forest Service and built by the Monarch Forge and Machine Works of Portland, Oregon, representing a broad single-tread caterpillar with attached snow-pontoon (Fig. 2) has been undergoing prolonged tests under average conditions in the southern Sierra. W. A. LANG, Chief Hydrographer, Southern California Edison Company, Los Angeles, relates the following experiences:

"I had an opportunity to make the first trip from Huntington to Florence Lake and on this occasion the 'Sno-Motor' carried 12 passengers in addition to the driver and approximately a ton

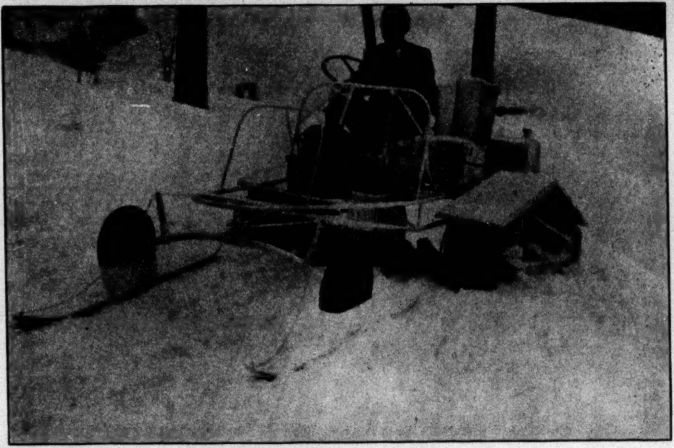


Fig. 1--Tucker motor-sled, caterpillar type

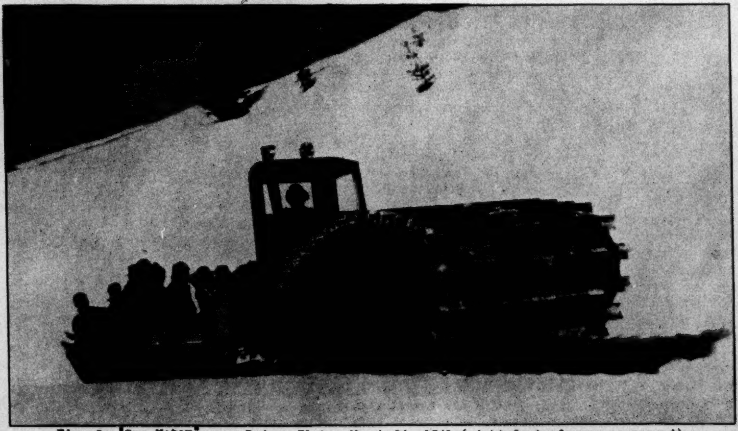


Fig. 2--'Sno-Motor' near Badger Flats, March 24, 1941 (eight feet of snow on ground) of food, baggage, and other material. We left Home Camp Creek at the west end of Huntington Lake about 6:30 a.m. and were on Kaiser Pass at about 10:30 a.m. In the early morning the crust of the snow was so hard that hardly any impression was left by the crawler or sled runner-plates, although it sank in about four to six inches later in the day. From Kaiser Pass to Florence Lake required another six hours including time out for lunch. In general, we followed the road, only making detours to avoid protruding rocks, fallen trees, and ravines, or bare spots. Snow-depths were approximately eight feet at Huntington Lake, 12 feet at Kaiser Pass, and three feet at Florence Lake.

"From time to time various members of the party jumped off the sled to walk in order to limber up, or warm up a bit. On the upgrade, regardless of whether the snow was soft or crusted, it was impossible to keep pace with the 'Sno-Motor' for any distance because, even though the 'Sno-Motor' was slow, the steady pace and exertion of climbing soon tired out the hiker. Going downhill or on the level it was possible to keep up with the motor by taking short cuts if necessary. However, all agreed that it was much easier to ride the 30 miles on the 'Sno-Motor' in about ten hours (including stops) than it would have been to walk the same distance, even without a pack.

"During the trip to Florence Lake the 'Sno-Motor' successfully negotiated grades of 55 per cent and in several instances ran along side-hill slopes of 25 per cent. Coming out a week later we had only two passengers and a 1,000-pound load. At that time we ran into a snow-storm and had about a foot or so of new wet snow on the pass. The 'Sno-Motor' performed equally as well, if not better, under this condition and it was possible to travel along side-hill slopes greater than 25 per cent owing to the holding qualities of the soft wet snow.

"About 75 gallons of gasoline were used in making the round trip. Since then the 'Sno-Motor' has traveled some 400 miles without any serious mechanical trouble although some minor changes have been made as experience was obtained in its operation. It was found necessary to reinforce the front end of the sled and to provide a drip-oiler on the roller-tracks."

Air-propeller sleds have been used in open areas but seem ill adapted to either steep slopes or forested areas. However, this type has been used satisfactorily in Colorado.

The Eliason motor-toboggan (Fig. 3) manufactured by the Four Wheel Drive Auto Company of Clintonville, Wisconsin, has been given strenuous tests at Camp McCoy, Wisconsin, during winter maneuvers of the Army, according to Link-Belt News [March, 1941], kindly forwarded to the Chairman by Professor CLARK AMENS of the University of Nevada.

"Traveling up hill on its own power, or down, and across level areas at speeds of up to 40 miles an hour, carrying three passengers, the new vehicle lends itself to a wide range of uses. Winter-sports lovers find it to be one of the greatest winter thrills yet experienced. Trappers can now tend trap-lines within a few hours, that ordinarily would require a week to cover. Utility-line-maintenance crews, who must 'track down' breaks on their lines off the highways, praise the time-saving ability of the new conveyance. Woodsmen, hunters, sportsmen, and others whose business or pleasure requires transportation in the snowy areas, find the new motor-toboggan a long-awaited means of affording a greater range of winter travel.

"The framework of the machine is similar to that of an ordinary toboggan except that a portion of the bed is an endless cleated composition-belt. This belt not only helps to give the craft buoyancy in all types of snow, but by a firm pressure it grips the snow or ice and thus provides the traction for propulsion. The cleated belt (Figs. 4 and 5) is driven through a three-speed transmission from a 25-horsepower air-cooled gasoline engine by sturdy Link-Belt Silverlink roller chains. Ordinarily the belt 'floats' over the snow at the same level as the bottom of the toboggan, but it can be lowered as much as eight inches to give traction over irregular ground or where snow is loosely packed and deep. Under ideal conditions the toboggan can climb a grade of 35 per cent with ease. Moreover, it is relatively light."

Regarding this toboggan BESTOR ROBINSON writes: "The reference to snow-toboggans raises this question: The General Staff sent out to Donner Summit for testing an Eliasen motor-toboggan, which proved to have unusual value for traveling over unconsolidated snow at high rates of speed. Reports of its use by the Canadian Army confirm this conclusion. For conditions in our West certain basic changes were necessary and I recommended to the Army that it be turned over to the Forest Service for further development. Such an order has been made and funds have been made available for the necessary material for development."

Airplane--The old dream of going to the snow-fields by airplane has been revived by Professor H. P. BOARDMAN, Chairman, Nevada Cooperative Snow Surveys, who believes that the autogiro would be ideal for the purpose because of its ability to descend and arise vertically and maintain its position without forward movement. It can execute a 250-foot take-off without wind. Thus, large areas can be covered by a single party with slight fatigue within the period now required by several. A total view of the relative snow-area can likewise be obtained. An estimate of the cost of service by autogiro as compared with that by ski or motor-sled would be well worth while airplane service is now being considered by R. A. Work for more remote courses in Oregon.

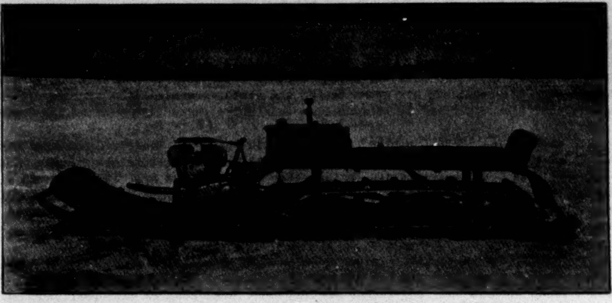


Fig. 3--Eliason motor toboggan

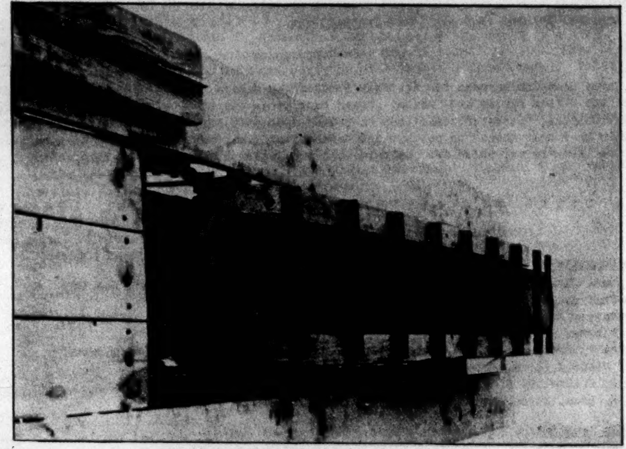


Fig. 4--Eliason motor toboggan cleated drive

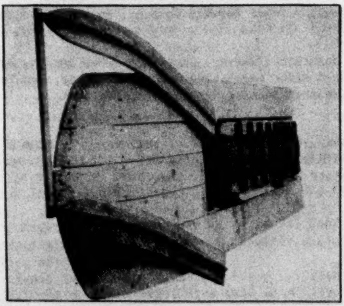


Fig. 5--Eliason motor toboggan steering ski

Regional meetings

Two Regional Meetings of the Section of Hydrology have been held in the West during the year--at Seattle during June 19-22, 1940, and at Sacramento during January 16-18, 1941--and in affiliation with them the usual sessions of the Western Interstate Snow-Survey Conference. The membership of the Conference has now grown to 533 and member-organizations to 154. The latter have shared either financially or by personnel in snow-surveying or the work of the Conference.

The regional meeting of the Section of Hydrology in the South Pacific Coast Area has now become an annual event and will be held next at the California Institute of Technology at Pasadena in January, 1942. But the meetings in the other Western areas are still only occasional. One is planned by the South Continental Divide Area at Salt Lake City, Utah, in June, 1942, in affiliation with the Pacific Division of the American Association for the Advancement of Science and another by the North Pacific Coast Area at Portland, Oregon, in 1943.

The Snow-Survey Conference meets in conjunction with the Section of Hydrology in all the Western areas, but in order to avoid the expense of publishing two Transactions in some years, it has been decided to hold only one formal meeting with large program each year and confine the other meeting to a dinner session. Fortunately the American Geophysical Union has granted the Western Interstate Snow-Survey Conference printing privileges with the Section of Hydrology and provides regional volumes of their joint Transactions.

The Snow-Conferences

The three Snow-Conferences now actively functioning make a complete coverage for the snow-section of the United States and Canada. Their purpose is the study of snow and even ice in all their relationships. Research-Committees have been appointed for all. Acting members and acting chairmen have been chosen to perform the tasks of original members who have been called to National Defense service; these are Chairman West and Chairman Hathaway, and Member R. C. Farrow.

COMMITTEES OF EASTERN SNOW-CONFERENCE, 1940-41

(Conference organized at Boston, September 16, 1940)

Executive Committee

Chairman: E. S. Cullings, Black River Regulating District, Watertown, New York
Vice-Chairman: Merrill Bernard, U. S. Weather Bureau, Washington, D. C.
Secretary: Hollister Johnson, U. S. Geological Survey, Water Resources Branch, Albany, New York
Charles F. Brooks, Blue Hill Meteorological Observatory, Milton, Massachusetts
C. H. Diebold, U. S. Forest Service, Washington, D. C.
John B. Drisko, U. S. Engineers Office, Providence, Rhode Island
Paul L. Bean, Union Water Power Company, Lewiston, Maine

Committee on Records

Arthur W. Harrington, U. S. Geological Survey, Water Resources Branch, Albany, New York
Philip W. Thomas, Rumford Falls Power Company, Rumford, Maine
Harry M. Nelson, New England Power Service Company, Boston, Massachusetts

Equipment Committee

H. B. Kinnison, U. S. Geological Survey, Water Resources Branch, Boston, Massachusetts
Edward H. Sargent, Hudson River Regulating District, Albany, New York
E. J. Christie, U. S. Weather Bureau, Hartford, Connecticut

Committee on Research

Chairman: G. A. Hathaway, Office of Chief of Engineers, U. S. A., Washington, D. C.
Acting Chairman: C. F. Merriam, Pennsylvania Water and Power Company, Baltimore, Maryland
J. S. Sweet, U. S. Weather Bureau, Albany, New York

COMMITTEES OF NORTH CENTRAL STATES SNOW-CONFERENCE, 1940-41

(Organized at Detroit, December 12, 1940)

Executive Committee

Chairman: M. W. Kyler, Wisconsin Valley Improvement Company, Wausau, Wisconsin
Vice-Chairman: H. Merrill Wills, U. S. Weather Bureau, East Lansing, Michigan
Secretary: V. G. Hawkins, U. S. Engineers, War Department, Detroit, Michigan
A. J. Connor, Meteorological Services, Department of Transports, 315 Bloor Street West, Toronto, Ontario
W. U. Garstka, Project-Supervision, U. S. Soil Conservation Service, East Lansing, Michigan
F. C. Christopherson, U. S. Geological Survey, Madison, Wisconsin
Hilbert Hill, Northern States Power Company, Minneapolis, Minnesota

Committee on Records

Chairman: E. W. Carlson, Hydrological Service, Cincinnati, Ohio
Paul R. Speer, District Engineer, U. S. Geological Survey, St. Paul, Minnesota
Chas. E. Harger, Wisconsin Michigan Power Company, Appleton, Wisconsin

Committee on Equipment and Field-Methods

Chairman: C. V. Youngquist, U. S. Geological Survey, Columbus, Ohio
A. G. Carson, Chief Engineer, Wisconsin Public Service Corporation, Green Bay, Wisconsin
E. P. Howell, Superintendent, Defiance Division, The Toledo Edison Company, Toledo, Ohio

Committee on Research

Chairman: J. I. Perrey, U. S. Geological Survey, Indianapolis, Indiana (recently resigned for Army service)
W. U. Garstka, Project-Supervision, U. S. Soil Conservation Service, East Lansing, Michigan
C. G. Bates, Principal Silviculturist, Lake States Experiment Station, U. S. Forest Service, University Farm, St. Paul, Minnesota

Program-Committee

Chairman: H. Merrill Wills Co-Chairman: W. U. Gerstka
E. W. Carlson; C. V. Youngquist

COMMITTEES OF WESTERN INTERSTATE SNOW-SURVEY CONFERENCE, 1940-42

(Organized at Reno, February 18, 1933)

Executive Committee

General Chairman: Fred H. Paget

North Continental Divide Group

Regional Chairman: O. W. Monson, Irrigation Engineer, Montana State College, Agricultural Experiment Station, Bozeman, Montana
Lynn Crandall, Watermaster, District No. 36, U. S. Geological Survey District Engineer, Idaho Falls, Idaho
Harry T. Gisborne, In Charge of Forest Protection, Northern Rocky Mountain Forest and Range Experiment Station, Missoula, Montana
James C. Marr, Irrigation Engineer, Division of Irrigation, U. S. Soil Conservation Service, Boise, Idaho
Walter E. Johnson, In Charge of Snow Surveys in Chelan and Spokane Basins, Washington Water Power Company, Spokane, Washington

South Continental Divide Group

Regional Chairman: George D. Clyde, Dean of Engineering and Mechanic Arts, Utah State Agricultural College, Logan, Utah
R. L. Parshall, Senior Irrigation Engineer, U. S. Soil Conservation Service, Fort Collins, Colorado
Harry L. Potts, Water Rights Engineer, Denver Water Board, Denver, Colorado
J. Cecil Alter, Meteorologist, In Charge of U. S. Weather Bureau, Salt Lake City, Utah (Cincinnati, Ohio, after September 1, 1941)
Ashton R. Codd, Hydrologic Supervisor, River and Flood Division of the U. S. Weather Bureau, Portland, Oregon (transferred from Salt Lake City since election)

North Pacific Group

Regional Chairman: George G. West, Chief of Hydrology Section, U. S. Army Engineers, Portland, Oregon

Acting Chairman: R. A. Work, Associate Irrigation Engineer, Division of Irrigation, U. S. Soil Conservation Service, Medford, Oregon

R. C. Farrow, Chief Hydraulic Engineer, Water Rights Branch, Department of Lands, Victoria, British Columbia

Phil E. Church, Assistant Professor of Geography and Meteorology, University of Washington, Seattle, Washington

G. H. Canfield, District Engineer, U. S. Geological Survey, Portland, Oregon

S. H. Frame (acting member), Hydraulic Engineer, Water Rights Branch, Department of Lands, Victoria, British Columbia

Norbert H. Leupold (acting member), U. S. Engineer's Office, 500 Pittock Block, Portland, Oregon

South Pacific Group

Regional Chairman: Fred H. Paget, Associate Hydraulic Engineer, Division of Water Resources, California State Department of Public Works, Sacramento, California

H. P. Boardman, Professor Emeritus, Civil Engineering, University of Nevada, Reno, Nevada

James E. Jones, Civil Engineer, Los Angeles Department of Water and Power, Los Angeles, California

Joseph Kittredge, Jr., Professor of Forestry and Forest Ecology, Agricultural Experiment Station, University of California, Berkeley, California

W. A. Lang, Chief Hydrographer, Southern California Edison Company, Los Angeles, California

Committee on Research

Chairman: J. E. Church, Nevada Agricultural Experiment Station, Reno, Nevada
George D. Clyde, Utah State Agricultural College, Logan, Utah
R. L. Parshall, U. S. Soil Conservation Service, Fort Collins, Colorado
Merrill Bernard, U. S. Weather Bureau, Washington, D. C.
Joseph Kittredge, Jr., University of California, Berkeley, California
R. A. Work, U. S. Soil Conservation Service, Medford, Oregon

Cooperation

The question of closer cooperation has already been informally raised by correspondence between the three Conferences. MERRILL BERNARD believes that only general good would accrue to the snow-interests of the country through closer organization. He continues, "I am not an advocate of over centralized organization. I believe that differences in emphasis on the importance of snow, the marked distinctions in objective, technique, and the decided difference in the nature of the problem to be solved--all point to the desirability of maintaining the Conference as the organization-unit. Nevertheless, for a number of reasons, I am convinced a National Meeting would be profitable to all concerned at this time. Such a Conference would necessarily have to be held at some central point, such as Denver or Chicago. Its financing would present a problem for which I have not at this time the suggestion of an answer."

E. S. CULLINGS feels that the works and interests of the Regional Snow-Conferences will be local and reasonably well served through the existing organizations:

"It seems to me that a general meeting of all the Snow-Conferences would be very difficult to arrange. The chief problem would be that of traveling expense for those who might wish to attend the meeting. In my own organization I do not see how the expense of a trip to Chicago or Denver could be justified, and I should not feel able to attend such a meeting at my own expense. It seems quite likely that many others in the New England States would meet with the same difficulty. Would it not be possible to arrange a smaller and more limited conference at the annual meeting of the American Geophysical Union?"

Although the Annual Meeting of the Union in Washington, D. C., is held far from the West, a first step toward a National Convention could be taken by arranging a Conference of snow-representatives there. If desired, a more formal step could be taken by authorizing an Advisory Committee consisting of the Chairmen of the Executive Committees of the three Conferences to make recommendation regarding the assignment of projects of mutual interest.

The various Committees of the three Conferences, particularly the Research-Committees, can gain much by correspondence.

Publicity--teaching

Publicity is increasing. The press eagerly publishes the various forecasts from the preliminary to the final. Life Magazine is considering the publication of a feature article on the New science of snow-surveying and the season's outlook for water.

Even raw data were urgently requested by the Carson River ranchers before risking their alfalfa-seed on new plantings. Agricultural economists seek forecasts before recommending loans on prospective crops.

The University of Nevada has made snow-surveying and forecasting stream-flow a part of its program in hydrology but its present sponsor, Professor WARREN O. WAGNER will be absent for the coming year on defense-engineering duties in Hawaii.

The third annual ski and snow-survey training course for Forest Service officials in the Sierra Nevada Area was held in the Mono National Forest at Galena Creek, January 6-9, 1941. The attendance a year ago was 33, this year 60. In addition to the courses in skiing and snow-surveying, classes were given in first-aid applicable to winter-sports injuries. Entertainment included motion-pictures and informal evening programs. The more proficient skiers made the trek over Mount Slide to Lake Tahoe. The Mono Forest will make the school a permanent feature.

By the generous support of contributing organizations 2,600 copies of the Transactions of the Regional Meetings of the American Geophysical Union are distributed to those interested in the problems of snow. Copies are being reserved also for the members of the International Commission of Snow and Glaciers when the world is able to start forward again.

The Japanese sound-film "The formation of snow-crystals," by Professor UKITIRO NAKAYA, was presented during the year before the Regional Meeting at Seattle, the Meteorological Seminar at Moorhead, Minnesota, and the Southern California Edison Company at Los Angeles. Lack of proper projection-equipment prevented its use where desired elsewhere.

The Swiss film, "Snow and avalanches," is 16-mm and silent. It can be shown without difficulty and should be seen by all interested in snow transport.

Film-instruction has become a habit at the Regional Meetings of the Section of Hydrology of the Union and the Western Interstate Snow-Survey Conference. In addition to the film on "The formation of snow-crystals" there were shown at Seattle the "Story of electric service from the snow-fields to the home" by the Washington Water Power Company, "Snow-surveying in the Cascades" by R. A. WORK, "Snow-sports in the Northwestern Parks" by R. D. WATERHOUSE, and a color-film on "Snow-surveying in the Central Sierra" by WALTER HERZ; the last was shown also at Sacramento.

A New Hampshire Winter Map is being published by the State Planning and Development Commission. Travel News of the United States Travel Bureau summarizes its qualities as follows:

"The map shows the location of more than 75 winter-sports centers, 50 places recommended for ice-fishing, main highways and snow-train lines, and other features. Text on the reverse side describes the facilities available for skiing and other winter sports at each of the centers, and lists the water-bodies recommended by the Fish and Game Department for ice-fishing."

Publications

The Union of Soviet Socialist Republics and the United States have produced the greatest number of publications during the year, the former unfortunately almost wholly in Russian and therefore "closed books" to most readers. Some have come from England, Germany, Japan, New Zealand, Canada, and Switzerland. The Swiss have been extremely active in the study of avalanche forecasting, primarily because their defense takes them to the mountain slopes.

Summary of leading publications--Selected for excerpt is the paper by Koloskow on the "Method of determining, and the cartography of, atmospheric precipitation" and the "Handbook on avalanches" by the Swiss Snow and Avalanche Commission and Parsenn Service.

Report by CHARLES F. BROOKS on "It is time to test and improve the method of determining, and the cartography of, atmospheric precipitation" by P. J. KOLOSKOW

"Of most general interest in foreign publications is, perhaps, the above paper that appeared in Russian in Meteorologia i Hydrologia [Moscow and Leningrad, No. 1, pp. 114-116, 1938] and which has now been made more widely available as to content through a summary in German by H. STOLTENBERG [Ann. Hydrog. Mar. Met., pp. 140-141, April, 1940]. The main points, from Stoltenberg's abstract are:

"(A) The errors of present-day methods of determining and mapping precipitation are: (1) The 'standard' rain-gage in use over meteorological networks does not catch fully the precipitation that reaches the Earth's surface. (2) In a wind of two to five meters per second the deficiency is about ten per cent; at six to nine meters per second, 20 per cent. (3) In northwest

Kasakstan and in the Volga Region, the gage fails to catch 70 to 100 per cent of the snow-precipitation; in the polar regions, however, more than 150 per cent of the annual precipitation is caught as 'snow-precipitation' (snowfall + drift). (4) The uncounted 'horizontal precipitation' (fog-drip and rime) may in forested regions equal and exceed the vertical precipitation caught in the horizontal surface of the rain-gage. (5) With inclined fall of hydrometeors in regions of broken relief the slopes of differing exposure receive precipitation-amounts differing appreciably even though the catches in the precipitation-gages with horizontal receivers may be the same. (6) Precipitation is subject to division into vertical zones and increases with height up to a mean line of the zone of the rain-clouds. The location of rainfall-stations mostly in depressions, the incompleteness with which watersheds are covered, and their almost complete absence from the mountains seem to be the source of a very large minimization of precipitation on maps, which are drawn on the method of linear interpolation.

"(B) Needed improvements of method: (1) Suitable methods and adequate apparatus need to be exactly defined--especially to include the measurement of 'horizontal precipitation' in areas of frequent fog. (2) The measurement of the so-called 'concrete precipitation' in areas of broken relief needs to be newly organized, where the actual wetting by precipitation falling on a slant depends in very strong measure on the exposure of the slope. (3) Work out adequate complete rules in cartographic methods for precipitation: (a) Past records should be corrected for wind-loss of rain and especially snow-catch; (b) isohyets should be drawn with recognition of orography and the principle of differences of precipitation with altitude; (c) forest-areas should be outlined where an additional appreciable wetting by 'horizontal precipitation' is possible; (d) areas of broken relief should be outlined, to show where large deviations from the general precipitation may be expected on slopes of different exposure.

"The author believes that the improvements recommended can be realized."

Report on "Lawinen: die Gefahr für den Skifahrer--Ratschläge zur Beurteilung der Gefahr und Bekämpfung von Unfällen" (bearbeitet von der Schweiz. Schnee- und Lawinenforschung und dem Parsenndienst, copyright by Aschmann and Scheller AG., Zürich, Switzerland, 114 pp.)

As indicated in the title, "Lawinen" is a handbook for judging the danger of avalanches and combatting accidents from them. The book contains a brief analysis and description of snow-types with abundant snow-landscapes, other illustrations, and charts. The subjects treated are briefly as follows:

Snow--origin, deposition, transformation, settling, and plasticity.

Types of snow-cover--New snow, old snow (temperature relationships in the snow-cover and relative density and porosity).

Classification of avalanches--Uncompacted avalanches, wind-slab avalanches: (1) Influence of cohesion and friction; (2) forms of movement--pure earth-movement and pure air-movement, such as snow-dust avalanches and mixed movement.

Estimating avalanche-peril--(1) Influence of wind, temperature, radiation; (2) topography; (3) testing snow-cover--cohesion of uncompacted snow, tension of crusts, age of snow.

Avoiding avalanches--(1) Avalanche forecasting; (2) route-marking; (3) closing dangerous areas; (4) precautionary measures in traversing avalanche-dangerous slopes; (5) behavior when caught by avalanche.

Removing potential avalanches--(1) Treading down an avalanche; (2) loosing avalanches with aid of explosives.

Obstructions against avalanches--Diversion, blocking, prevention at source.

Rescue-Service--(1) Apparatus; (2) the avalanche dog; (3) rescue-routine; (4) sixteen examples of avalanche-accidents.

Honors

The John Deere Medal has been bestowed this year on R. W. TRULLINGER, Assistant Chief, Office of Experiment Stations, United States Department of Agriculture, for greatest service in the advancement of agriculture during the year. To the Chairman of the Committee on Snow he will always be remembered as one who understood.

Death

Two members of the United States Forest Service have died in the performance of duty: LEO M. MAYFIELD, in Utah, 1939, and KARL J. WILKINSON, in Nevada, 1941. Like the loss of the Titanic, their death will safeguard the lives of others.

Not as deaths but as tributes are the following citations given, for they all died at the end of life's trail: ARTHUR L. SMITH, Nevada Agricultural Experiment Station, Chief Assistant in the development of snow-surveying; WILLIAM TOYN and THOMAS TOYN, United States Forest Service, Snow-Surveyors in the Ruby Mountains, Nevada; BENJAMIN C. KADEL, United States Weather Bureau, formerly in charge Wagon-Wheel Gap Experiment Station and designer of the Kadel snow-tube for tapioca-snow; Dean FREDERICK H. SIBLEY, College of Engineering, University of Nevada, who believed in and encouraged snow-surveying as a basic science.

To these should be added J. E. PHILLIPS of the Los Angeles Department of Water and Power, one of the pioneers in establishing a snow-survey system for the Los Angeles Aqueduct.

Values

In these days when all are seeking to serve the National welfare, it is fitting to close this report with the motto on the reverse of the Federal-State Cooperative Snow-Survey forecasts:

"A rational approach to the research-problem of forecasting flow of streams necessary for irrigation, domestic, and municipal water-supply, hydroelectric power-generation, navigation, mining, and industry--A National-Defense Unit."

Supplementing this unit are snow-pleasures, acting when winter seems most depressing, to keep a nation fit.

Appreciation

Appreciation is expressed by the Committee particularly to the Nevada Agricultural Experiment Station that has provided clerical assistance, and to the various organizations that have cooperated so fully in making the Committee a center of guidance. The cooperative spirit of all interested in the fields of snow and ice has been remarkable.

Nevada Agricultural Experiment Station,
Reno, Nevada, May 31, 1941

ADDENDUM

The following remarks regarding discussion by Dr. Brooks [p. 961] were received August 29, 1941, too late for insertion in appropriate place:

Dr. H. G. DORSEY, JR.--"I agree quite heartily with Dr. Brooks' interpretation of the situation at East Base as regards precipitation. I think there is one case which he may have overlooked, namely:

"At times of cyclonic easterly gales (northeast, discounting local topographic effects), with an alto-stratus or nimbo-stratus overcast, there would frequently be varying amounts of drift, depending on the temperature and type of snow-surface. Fallstreifen or virga would be visible as low as 2,500 to 4,000 feet, resembling curtains of falling snow, hiding nearby mountain peaks, yet none of this precipitation would survive evaporation and reach the surface after sinking into the lower föhn-wind. It was presumed that the cyclonic precipitation reached the surface further west, away from the local föhn-effects. This opinion was verified on several occasions by reports from vessels of the Expedition about 100 miles offshore."

APPENDIX A--LIST OF CURRENT PUBLICATIONS ON SNOW AND ICE

Carl Elges, Ralph W. Burhoe, and L. Jacchia

GENERAL

S. K. Banerji, Kinematical methods in weather forecasting, Proc. Nation. Inst. Sci. India, v. 5, No. 1, pp. 139-165, 1939.

J. H. Bretz, Earth sciences: Meteorology, oceanography, geology, Wiley, 1940, 260 pp.

W. J. Humphreys, Physics of the air, McGraw-Hill Book Co., 1940, 676 pp.

Hydrologische Bibliographie für 1938, Deutsches Reich. Landesanstalt für Gewässerkunde und Hauptnivellements, Jahrg. 3, Berlin, 1940, 105 pp.

Klimat USSR (Climate of the USSR, Part 2, Monthly mean barometric pressure and wind-directions), Geophys. Cen. Obs., Atlas, Leningrad, 1932.

F. E. Matthes, New international commission of snow and glaciers, Nature, v. 145, pp. 753-754, 1940.

P.-L. Mercanton, Schnee- und Gletscherbeobachtungen 1939 in den Schweizeralpen, Die Alpen, H. 6, 1940.

J. Namias, An introduction to the study of air mass and isentropic analysis, 5th revised and enlarged ed., with contributions by Tor Bergeron, Bernhard Haurwitz, (and others). Edited by Robert G. Stone, Milton, Mass., Amer. Met. Soc., 1940, 232 pp., (bibliog., pp. 176-227).

S. Petterssen, Weather analysis and forecasting; a textbook on synoptic meteorology, McGraw-Hill Book Co., 1940, 505 pp.

R. G. Stone, Addendum to bibliography on snow and ice, Trans. Amer. Geophys. Union, Part 4, pp. 631-635, 1939.

M. M. Vasiljevski', On the structure of a hydrogeological map of the USSR, Priroda (Nature), pub. by Acad. Sci., Issue 4, p. 54, 1940 (in Russian).

E. W. Woolard, Physical interpretation of the weather, Smithsonian Rept., 1939, pp. 223-239.

SNOW

(1) General

David L. Arenberg, Riming program for 1940, Mt. Wash. Obs. News Bull., No. 8, pp. 5-6, January 1941.

H. Bade, Snow stars, photography, Photo Tech., v. 3, p. 51, January 1941.

Merrill Bernard and A. R. Codd, Progress-report on mountain snowfall-program of the Weather Bureau, Trans. Amer. Geophys. Union, Part I, pp. 122-130, 1940.

R. Billwiller, Der Firnzuwachs pro 1937/38 in einigen schweizerischen Firngebieten, 26, Ber. Zürich. Gletscherkommission V. J.-Schrift NGZ, 1939, 331 pp.

C. E. Britton, Heavy snows on May 14, 1924, Met. Mag., v. 75, No. 892, p. 72, 1940.

D. Burd, Photo near Norden, Sierra Club Bull., v. 26, p. 94+, February 1941.

J. E. Church, Annual report of the committee on snow, 1939-1940, Trans. Amer. Geophys. Union, pp. 374-396, 1940.

P. E. Church, The snow cover of Washington State, Bull. Amer. Met. Soc., v. 22, No. 2, p. 64, 1941.

The coloured snow fall, Priroda (Nature), pub. by Acad. Sci., Issue 10, p. 63, 1940 (in Russian).

Charles A. Connaughton, Research on snow by the U.S. Forest Service, Trans. Amer. Geophys. Union, Part 3, pp. 920-925, 1940.

M. Edgelow, Snowfall, Queen's Q, v. 47, No. 3, pp. 339-340, August 1940.

E. Ekhart, Zur Kenntnis der Schneeverhältnisse der Ostalpen, Gerlands Beitr., Bd. 56, p. 321, 1940.

G. Epifanskii, The observation of snow crystals, Pogoda (Weather), No. 12, p. 708, December 1940 (in Russian).

C. Elges, Addendum to report of Committee on Snow, 1939-40--list of current publications on snow and ice, Trans. Amer. Geophys. Union, Part II, pp. 750-779, 1940.

F. Fabiańics, Die Schneeverhältnisse von Budapest, Idöj., v. 44, p. 191, 1940.

W. Findeisen, Flugmeteorologische Schneebeobachtungen, Met. Zeit., v. 56, pp. 429-435 (abs. p. 429), 1939.

N. H. Galakhov, Snow cover in the forest, Met. i Hydro., No. 3, pp. 3-18, 1940 (in Russian).

G. Greim, Der Schneefall in Hessen 1901-1930, Met. Zeit., v. 57, p. 46, 1940.

G. Greim, Der Schneefall in Hessen in den Jahren 1901-1930, Germany, Reichsamt für Wetterdienst, Wissensch. Abhandl., Bd. 5, H. 8, Berlin, 1939, 26 pp.

E. Gherzi, Quelques données sur la distribution de la neige en Chine, Internat. Union Geod. and Geophys., Bull. Assoc. Sci. Hydrol., No. 23, pp. 133-136, 1938.

D. Haig-Thomas, Tracks in the snow, Oxford Univ. Press, N. Y., 1939, 287 pp.

SNOW--Continued

(1) General--Concluded

E. L. Hawke, The snowstorm and drifts of January 26-29, 1940, in the Northern Chilterns, Q. J., v. 66, No. 285, pp. 152-153, 1940.

W. Heybrock, Schneegrenze und Firnverhältnisse am Gran Sasso d'Italia (Abruzzen) im Herbst 1938, Zeitschrift für Gletscherkunde, Bd. 27, H. 1-2, pp. 171-176, 1940.

An ice-like snow, Priroda (Nature), pub. by Acad. Sci., Issue 5, p. 68, 1940 (in Russian).

C. Kassner, Schneefall im Ballsaal, Met. Zeit., v. 57, pp. 93-95, 1940.

E. Kossinna, Die Schneedecke der Ostalpen, Met. Zeit., v. 57, p. 85, 1940.

F. A. Kravchenko, The fall of yellow snow, Pogoda (Weather), No. 1, p. 14, May 1940 (in Russian).

E. Lau, Schnee im Wärmehaushalt der Erde Zeits. f. d. ges. Naturwiss., 11/12, 1940.

A. Lebed, The role of snow cover in the preservation of winter wheat, Pogoda (Weather), No. 11, pp. 16-17, November 1940 (in Russian).

F. Linke, Entstehung des Büsserschnees, Zeits. f. angew. Met., Das Wetter, No. 6, p. 182, 1940.

G. Manley, Snowfall in the British Isles, Met. Mag., v. 75, No. 891, pp. 41-48, 1940.

Mesacny prehl'ad meteorologických pozorovani, vodných stavov a prietokov, Státny Hydrologický a Meteorologický Ustav, Bratislava (Monatsberichte über die meteorologischen Beobachtungen, Flusswasserstände und Abflüsse, Pressburg), January 1940 +. Contains water content of snowdeck at 36 measuring stations, charts of depth of snow on the ground.

The miracle of snow crystals, Taylor Rochester, summer ed., v. 30, No. 1, pp. 32-33, 1940.

V. G. Nesterov, To the question about influence of forest on the snow cover, Met. i Hydro., No. 3, pp. 136-139, 1940 (in Russian).

Nevada Agricultural Experiment Station, Department of Meteorology, Annual Report, June 30, 1940.

N. A. Pavlov, Attrition on snow surface, Met. i Hydro., No. 4, pp. 115-118, 1940 (in Russian).

M. Pinkhof, Ijzel en sneeuw op 14 Maart 1940, Hemel dampkr., Groningen, v. 38, pp. 165-168, 1940.

R. Plandé, Neiges et glaces d'aujourd'hui dans les Pyrénées, Revue géophysique des Pyrénées et du sud-ouest, Tome 10, fasc. 2, pp. 85-106, 1939.

J. H. Stoeckeler and E. J. Dortignac, Snowdrifts as a factor in growth and longevity of shelterbelts in the Great Plains, Ecology, v. 22, pp. 117-124, April 1941.

R. G. Stone, The distribution of the average depth of snow on ground in New York and New England (II): Curves of average depth and variability, Trans. Amer. Geophys. Union, Part 2, pp. 672-750, 1940.

S. Tazina and Y. Mimuro, Some studies on the thawing of snow on the ground, J. Met. Soc. Japan, second series, v. 18, No. 7, p. 24, 1940.

F. Thone, Falling frozen water, Sci. News Letter, v. 39, p. 31, January 11, 1941.

Thunderstorm, graupel, snow, and a rainbow, Mt. Wash. Obs. News Bull., No. 8, pp. 7 and 9, January 1941.

U. S. Dept. of Agric., July 1940, Snow makes a good blanket, Bull. Amer. Met. Soc., v. 21, No. 10, p. 396, December 1940.

R. D. Waterhouse, Snow-activities of the National Park Service, Trans. Amer. Geophys. Union, Part I, pp. 134-136, and Part III, p. 920, 1940.

B. P. Weinberg, List of latest publications of U.S.S.R. on ice and snow, Trans. Amer. Geophys. Union, Part II, pp. 757-779, 1940.

C. C. Williford, Black dust with hail, snow, and rain, Bull. Amer. Met. Soc., v. 22, No. 3, pp. 122-123, 1941.

R. A. Work, A plan for the study of snow-cohesion and snow-loads in estimating the necessary strength of roofs against snow-overload, Trans. Amer. Geophys. Union, Part 3, p. 901, 1940.

C. Wright, A collection of sixteen photographs, following p. 14, Sierra Club Bull., v. 26, February 1941.

(2) Precipitation and evaporation

Abnormal rainfall in Texas, Eng. News Rec., v. 126, No. 1, p. 37, 1941.

David L. Arenberg, The formation of small hail and snow pellets, Bull. Amer. Met. Soc., pp. 113-116, March 1941.

M. Bernard, Chairman, Committee on rainfall, 1939-40, Trans. Amer. Geophys. Union, Part 2, pp. 370-373, 1940.

Merrill Bernard, and Charles F. Ruff, Reliability of station-year rainfall frequency determinations: Discussion, Proc. Amer. Soc. Civ. Eng., v. 67, No. 3, pp. 474-482, 1941.

Better evaporation data sought, Eng. News Rec., v. 125, No. 25, p. 831, 1940.

SNOW--Continued

(2) Precipitation and evaporation--Continued

G. J. Bouyoucos and A. H. Mick, Electrical resistance method for the continuous measurement of soil moisture under field conditions, Mich. Sta. Tech. Bull., No. 172, 1940.

C. F. Brooks, Further experience with shielded precipitation-gages on Blue Hill and Mount Washington, Trans. Amer. Geophys. Union, Part 2, pp. 482-485, 1940.

J. E. Church, Meteorological studies, Greenland expeditions of the University of Michigan. A. Climate and evaporation in Alpine and Arctic zones; B. Temperatures of Arctic soil and water, from the reports of the Greenland Expeditions of the Univ. of Mich., Part 2, pp. 1-61, 1941.

K. Clarke-Hafstad, Reliability of station-year rainfall frequency determinations, Proc. Amer. Soc. Civ. Eng., v. 66, No. 9, pp. 1603-1622, 1940.

A. R. Codd, Calcium-chloride solutions in the operation of precipitation-gages, Trans. Amer. Geophys. Union, Part 3, pp. 913-915, 1940.

G. N. Cox, Study of evaporation from water surfaces; abstract, Pub. Works, v. 72, p. 18, January 1941.

E. Ekhart, Beitrag zur Kenntnis der Niederschlagsverhältnisse der Hochalpen, Zeit. f. Angew. Met., Das Wetter, No. 10, pp. 311-321, 1939.

C. Elges, Problem of using calcium-chloride in precipitation-gages, Trans. Amer. Geophys. Union, Part 3, pp. 911-913, 1940.

N. N. Galakhov, Snow cover in the forest, Met. i Hydro., No. 3, pp. 3-17, 1940 (in Russian).

E. B. Garrett, A once-in-a-hundred-years rain, U. S. Dept. Agric., Soil Conservation, pp. 228-230, February and March 1941.

K. Hasimoto and others, On the effect of Earth's surface on evaporation, J. Met. Soc. Japan, second series, v. 18, No. 8, p. 29, 1940.

P. V. Hodges, Reliability of station-year rainfall frequency determinations; discussion, Proc. Amer. Soc. Civ. Eng., v. 67, No. 1, pp. 129-132, 1941.

C. J. Jarvis and H. W. Broad, Reliability of station-year rainfall frequency determinations; discussion, Proc. Amer. Soc. Civ. Eng., v. 67, No. 2, pp. 255-259, 1941.

I. I. Kassatkin, On the question of the influence of irrigation on the amount of precipitation, Met. i Hydro., Issue 8, p. 90, August 1940 (in Russian).

C. Kassner, Schneefall in- und ausser-halb der Grossstadt, Zeit. f. angew. Met., Das Wetter, No. 10, pp. 336-338, 1939.

H. F. Kennison, Sixty-year rainfall record analyzed, Civ. Eng., v. 10, pp. 709-710, November 1940. Discussion, C. F. Johnson, v. 11, p. 118, February 1941.

J. Kittredge, Committee on evaporation and transpiration, 1939-40, Trans. Amer. Geophys. Union, Part 2, pp. 406-409, 1940.

W. W. Korhonen, Niederschlags- und Schneebeobachtungen in Finnland im Jahre 1938, Met. Jb für Finnland, Bd. 38, Teil 2, 96 pp.

Charles J. Lyon, Tree ring measurements in New England, summary (Tree rings forecast drought in New England in 1941), Bull. Amer. Met. Soc., v. 22, No. 5, p. 219, 1941.

T. Maeda, The effect of wind velocity on the measurement of rainfall by rain-gauges, J. Met. Soc. Japan, pp. 26-31, December 1939.

G. Manley, Snowfall in the British Isles, Met. Mag., v. 75, No. 891, pp. 41-48, 1940.

A. Marolda, Note sugli apparecchi evaporatori, Riv. Marittima, No. 10, Rome, 1939.

P.-L. Mercanton, Recherches de technique pluviométrique, Zurich. A. Schweiz. Met. Zent. Anst., v. 75, No. 8, 6 pp., 1938.

P.-L. Mercanton, Recherches de technique pluviométrique, III, Essais comparatifs sur le toit de la Station météorologique centrale, a Zurich. Ann.-der Schweiz. Met. Zentralanstalt, Anhang No. 9, 5 pp., 1939.

Natural water loss in selected drainage basins, Geol. Surv. W.-S. Paper 846, 1940.

V. G. Nesterov, To the question about influence of forest on the snow cover, Met. i Hydro., No. 3, pp. 136-139, 1940 (in Russian).

R. W. Powell, Evaporation of water from saturated surfaces, Engineering, v. 150, No. 3899, pp. 278-280, 1940.

Presence of hydrogen in the upper layers of the atmosphere and silvery clouds, Priroda (Nature), pub. by Acad. Sci., Issue 6, p. 94, 1940 (in Russian).

H. S. Riesbol, Report on exploratory study of rain-gage shields and enclosures at Coshocton, Ohio, Trans. Amer. Geophys. Union, Part 2, pp. 474-482, 1940.

A. Rohringer, Versuche mit Verdunstungsmesser neueren Systems, Az. Idöj., Budapest, v. 15, 1939, pp. 231-234, in Magyar; German summary, pp. 264-265.

D. I. Shasko, Water loss on transpiration by different agricultural cultures, Met. i Hydro., Issue 8, p. 60, August 1940 (in Russian).

K. Siomi and S. Yosida, Effects produced by wind on evaporation, J. Met. Soc. Japan, second series, v. 18, No. 6, p. 23, 1940.

SNOW--Continued

(2) Precipitation and evaporation--Concluded

A. Stickley, An evaluation of the Bergeron-Findeison precipitation theory, Mon. Weath. Rev., v. 68, No. 10, pp. 272-279, October 1940.

H. C. S. Thom, On the statistical analysis of rainfall-data, Trans. Amer. Geophys. Union, Part II, pp. 490-499, 1940.

C. W. Thornthwaite and B. Holzman, A year of evaporation from a natural land-surface, Trans. Amer. Geophys. Union, Part II, pp. 510-512, 1940.

Weather robots planned for inaccessible spots, Science, v. 92, supp. 6, July 26, 1940; Same: Sci. News Letter, v. 38, p. 51, July 27, 1940; Sci. Dig., v. 8, pp. 95-96, September 1940.

C. K. Wentworth, Ablation of snow under the vertical sun in Hawaii, Amer. J. Sci., v. 238, No. 2, pp. 112-116, 1940.

I. K. Zelemoi, On quantitative characteristic of snow storms, Met. i Hydro., No. 1-2, pp. 124-125, 1940 (in Russian).

(3) Snow-surveying

J. C. Alter, The mountain snow-survey: Its genesis, exodus, and revelation, Trans. Amer. Geophys. Union, Part III, pp. 892-899, 1940.

H. P. Boardman, A proposed snow-survey system for the Yakima Basin, Trans. Amer. Geophys. Union, Part III, pp. 878-887, 1940.

California Department of Public Works, California cooperative snow-surveys, Mon. Bull. Snow Sur. and Precip. Data, February to May, 1940, and February to May, 1941, Sacramento, 1940 and 1941.

California's snow patrol at work, Los Angeles Times, March 3, 1940.

J. E. Church, Map of western snow-survey systems, Trans. Amer. Geophys. Union, Part III, p. 874, 1940.

G. Crestani, Sulla riduzione dello spessore del manto nevoso in altezza di pioggia: Sullar densita della neve recente e sulle sue variazioni, Estratto dagli Annali dei Lavori Pubblici (gia Giornale del Genio Civile) Anno 1938, Fasc. 2, Roma.

G. Crestani, Sulla determinazione dell'equivalente in acqua e della densita della neve: Studio teorico-sperimentale, Estratto dagli Annali dei Lavori Pubblici (gia Giornale del Genio Civile), Anno 1937, Fasc. 6, Roma.

C. H. Diebold, Review of "Snow surveying by J. C. Marr", J. For., v. 39, p. 77.

The hydromike, "Quibble Scribbles" (niphometrology, snow-surveying), v. 4, No. 3, May 1941.

J. C. Marr and P. A. Ewing, Snow surveying, Soil Conservation, v. 5, No. 6, pp. 144-147, 1939.

J. C. Marr, Snow surveying, U. S. Dept. Agric., Misc. Pub. 380, p. 45, 1940.

Nevada snow and runoff surveys, Eng. News-Rec., p. 69, July 3, 1941.

F. H. Paget, California snow-survey assures an ample water-supply this year, Cal. Highways and Pub. Works, p. 4, May 1940.

F. H. Paget, First snow-survey completed, Cal. Highways and Pub. Works, v. 19, pp. 10-12, 1941.

R. C. Parshall, Forms for recording and reporting measurements, Trans. Amer. Geophys. Union, Part I-B, pp. 109-119, 1940.

J. V. Salo, A quantitative forecast-system of runoff based on snow-surveys at the mean elevation of the snow-cover in the Merrimack Basin, Trans. Amer. Geophys. Union, Part I, pp. 119-120, and Part III, pp. 858-870, 992-995, 1940.

Snow surveys show water supply available, Amer. City, v. 55, pp. 55-59, 1940.

F. Thone, Snow-surveys, Sci. News Letter, v. 37, p. 366, June 8, 1940.

To make snow-survey in Great Lakes area, Eng. News-Rec., p. 7, December 26, 1940.

O. Tryselius, A Short comparison between the Finnish and the Swedish snow samplers, reprinted from Geografiska Ann., Heft 3-4, 1940.

(4) Forecasting

P. L. Bean, A quantitative forecast-system for power and flood-warning in the Androscoggin River Basin, Maine, Trans. Amer. Geophys. Union, Part III, pp. 835-846, and discussion pp. 847-858, 1940.

M. Bernard, Forecasting of stream-flow from melting snow, Trans. Amer. Geophys. Union, Part III, p. 935, 1940

H. P. Boardman, G. G. Devore, and L. Sanford, Seasonal snow-survey and forecast of the stream-flow in Central Sierra Quadrangle, Nev. Coop. Snow-Surveys, April 1941.

SNOW--Continued

(4) Forecasting--Continued

H. P. Boardman, G. G. Devore, and L. Sanford (Forecast Committee), Nevada Cooperative Snow-Surveys--eastern slope, Central Sierra Nevada: Comparison of forecast and actual results, 1939, Trans. Amer. Geophys. Union, Part I, pp. 99-100, 1940.

G. D. Clyde, Utah cooperative snow-surveys and water-supply forecasts, Utah Agric. Exp. Sta. Mimeo. Sheet 226, April 1, 1941.

G. D. Clyde, Soil-moisture studies as an aid in forecasting runoff from snow-cover, Trans. Amer. Geophys. Union, Part III, pp. 871-874, 1940.

G. D. Clyde, Utah Cooperative Snow-Surveys: Comparison of forecasts and runoff for 1939 for State of Utah, Trans. Amer. Geophys. Union, Part I-B, p. 103, 1940.

E. H. Collins, Report on snow-surveys of 1939 in the Chelan Basin, Trans. Amer. Geophys. Union, Part III, pp. 887-892, 1940.

E. B. Debler, Forecast of inflow of Colorado River into Lake Mead at Boulder Dam, 1939, Trans. Amer. Geophys. Union, Part I, p. 104, 1940.

C. Elges and J. E. Church, Seasonal snow-survey and forecast of stream-flow in Humboldt quadrangle, Federal-State Coop. Snow-Surveys, Reno, Nev., March 1 and April 1, 1941.

C. Elges, Present trends in improving forecasting in the Humboldt Basin, Nevada, Trans. Amer. Geophys. Union, Part III, pp. 874-878, 1940.

C. Elges, Nevada Cooperative Snow-Surveys: Review of 1939 forecast results, Humboldt River Basin, Nevada, Trans. Amer. Geophys. Union, Part I-B, p. 100, 1940.

R. C. Farrow, Accuracy of forecasts in British Columbia in 1939, Trans. Amer. Geophys. Union, Part III, pp. 987-988, 1940.

R. C. Farrow, British Columbia Snow-Surveys: Report on snow-surveys and actual runoff in the Upper Columbia, Fraser, and Powell River basins for 1939, Trans. Amer. Geophys. Union, Part I, pp. 105-108, 1940.

Forecasting irrigation water supply, Taylor Rochester, Summ. Ed., v. 30, No. 1, pp. 28-29, 1940.

D. B. Freeman, Upper Missouri River forecasts at Fort Peck, 1938 and 1939, Trans. Amer. Geophys. Union, Part III, pp. 986-987, 1940.

D. B. Freeman, North Continental Divide: Comparison of forecast and runoff of the Upper Missouri Basin at Fort Peck Reservoir, 1939, Trans. Amer. Geophys. Union, Part I, pp. 104-105, 1940.

W. E. Johnson, Forecast and runoff, Lakes Coeur d'Alene and Chelan, 1939, Trans. Amer. Geophys. Union, Part III, pp. 984-986, 1940.

J. E. Jones, Los Angeles Department of Water and Power: Summary of 1939 forecast for Owens Basin, California, Trans. Amer. Geophys. Union, Part I, pp. 101-102, 1940.

W. A. Lang, Accuracy of forecasts at Huntington, Florence, and Shaver Lakes, Trans. Amer. Geophys. Union, Part I, pp. 102-103, 1940.

W. T. McFarlane, The accuracy of forecasts in the Pacific Northwest with reference only to the Bow and Saint Mary River basins, Trans. Amer. Geophys. Union, Part III, pp. 988-992, 1940.

W. W. McLaughlin, Problems of the Division of Irrigation in forecasting water-supplies, Trans. Amer. Geophys. Union, Part III, p. 920, 1940.

W. W. McLaughlin, Problems of the Division of Irrigation in forecasting water-supplies, Trans. Amer. Geophys. Union, Part I, pp. 131-133, 1940.

J. C. Marr, Accuracy of stream-forecasts on the Boise River, Idaho, 1939, Trans. Amer. Geophys. Union, Part III, p. 984, 1940.

O. W. Monson, Accuracy of stream-forecasts in Montana, Trans. Amer. Geophys. Union, Part III, p. 986, 1940.

Mountains hold flood secrets, Taylor Rochester, Fall Ed., v. 30, No. 2, p. 70, 1940.

P. A. Negichovsky, Method of short period forecasts of spring floods, Met. i Hydro., v. 12, p. 56, 1940 (in Russian).

F. H. Paget, California Cooperative Snow-Surveys, particularly western slope of Sierra Nevada: Report of 1939 forecasts, Trans. Amer. Geophys. Union, Part I, pp. 100-101, 1940.

R. L. Parshall, South Continental Divide: Comparison of forecasts and runoff in the Platte, Arkansas, and Rio Grande, and Colorado basins for 1939, Trans. Amer. Geophys. Union, Part I-B, pp. 103-104, 1940.

R. L. Parshall, Snow surveys permit forecasts of water, Colo. Agric. Exp. Farm Bull., v. 1, p. 16, April 1939.

R. L. Parshall, Relation of snow cover to irrigation supply, Through the Leaves, v. 26, pp. 32-35, March 1941.

H. Philipps, Zehn Jahre Grosswetterforschung, Naturwiss., p. 50, 1939.

SNOW--Continued

(4) Forecasting--Concluded

I. I. Schell, Foreshadowing this winter's precipitation in Montana, Bull. Amer. Met. Soc., v. 22, p. 24, 1941.

E. v. Schweidler, Über die Beziehungen zwischen extrem kalten Januaren und Sonnenaktivität, Met. Zs., No. 8, p. 308, 1940.

Snow up yonder means water for crops down here, Oregon Farmer, v. 64, p. 219, 1941; same article in Idaho Farmer, v. 59, p. 224, 1941.

Snow-surveys and irrigation-forecasts for Oregon, Div. Irr., Soil Conservation Serv. and Oregon State Eng. cooperating, Bull., February 1, March 1, and April 1, 1941.

Snow-surveys and irrigation-water forecasts for Columbia River Basin and other drainage-areas in Oregon and Washington, Div. Irr., Soil Conservation Serv., in coop. with States, March 1, April 1, and May 1, 1941.

Snow-surveys and irrigation-water forecasts for Missouri and Arkansas River basins, Div. Irr., Soil Conservation Serv., in cooperation with Colo. State College, April 1 and May 1, 1941.

Snow-surveys and irrigation-water forecasts for Rio Grande Basin, Div. Irr., Soil Conservation Serv., in cooperation with Colo. State College, April 1 and May 1, 1941.

Snow-surveys and precipitation-data and seasonal forecast of stream-flow, Cal. Coop. Snow-Survey, April 1, 1941.

R. Spitaler, Der Einfluss kalter und warmer Jahreszeiten in Sibirien auf die Niederschläge in Europa, Met. Zs., No. 8, pp. 302-304, 1940.

R. A. Work and J. H. Ryan, Accuracy of Oregon water-supply forecasts, 1936-1939, Trans. Amer. Geophys. Union, Part III, pp. 981-984, 1940.

R. A. Work, Forecast accuracy of water-supply as made from snow-surveys, Trans. Amer. Geophys. Union, Part III, p. 979, 1940.

(5) Normals and trends

S. Basu, Medium-range weather forecasts, Proc. Nat. Inst. Sci. India, v. 5, No. 1, pp. 43-165, 1939.

H. P. Gillette, Forecasting by means of climatic cycles, a paper presented Oct. 17, 1940, before the Pennsylvania Water Works Assoc. at its 45th annual meeting, Atlantic City, N. J., N. p., v. 6, p. 46, 1940.

W. Kaempffert, Since the eighteen thirties the climate has been warming up, Sci. Digest, v. 9, p. 33, June 1941.

W. Samuelson, Drouths do not run in cycles, West. Farm Life, v. 42, No. 23, p. 5, 1940. (Reports some of the findings of Harry Weekly of the North Platte, Nebraska State Exp. Farm, regarding drouth in Nebraska.)

Science in the news: Weather generally warmer since the turn of the century, Sci. Digest, v. 9, p. 24, January 1941.

A. Wagner, Klimaänderungen und Klimaschwankungen, Die Wissenschaft, Bd. 92, 1940, 227 pp.; reviewed in Ann. d. Hydro., Heft 10, pp. 369-370, 1940.

H. C. Willett, The Weather Bureau--Mass. Inst. of Technology five-day forecasts, Bull. Amer. Met. Soc., v. 21, No. 7, pp. 306-307, 1940.

(6) Runoff-factors: hydrology

M. Bernard, Application of hydrometeorology to engineering problems, Proc. Hydraulic Conf., Iowa City, Iowa, 1940, Univ. Iowa Studies, Bull. No. 20, pp. 69-80, 1940.

D. W. Cardwell, Runoff from small agricultural watersheds, Agric. Eng., v. 21, No. 12, pp. 479-482, 1940.

G. D. Clyde, Soil-moisture with reference to runoff, Trans. Amer. Geophys. Union, Part I, p. 119, 1940.

Compilation of rainfall and run-off from the watersheds of the Texas Agricultural Experiment Station, Substation No. 7, Spur, Texas, 1928-38, U. S. Dept. Agric., Soil Conservation Serv., Tech. Pub. 35, in coop. with Tex. Agric. Exp. Station, 1940.

G. N. Cox, A summary of hydrologic data Bayou Duplantier Watershed 1933-1939, Univ. Bull., La. State Univ., v. 32, N. S., 37 pp., 1940.

R. H. Elliott and L. K. Sherman, Unit-hydrograph, Trans. Amer. Geophys. Union, Part III, pp. 953-966, 1940.

A. P. Fedosseev, On the question of determining the field water capacity of the soil, Met. i Hydro., v. 11, p. 96, 1940 (in Russian).

J. Girand, Water supply on upper Salt River, Arizona, Proc. Amer. Soc. Civ. Eng., v. 65, pp. 1675-1686, 1939, discussion, v. 66, pp. 553-556, 1940.

F. L. Grant, The probability-viewpoint in hydrology, Trans. Amer. Geophys. Union, Part I, pp. 7-13, 1940.

J. M. Holmes and W. H. Maze, Rain runoff dispersion and soil conservation, Pub. in Geog., Univ. Sydney, N. S. W., No. 3, 31 pp., 1940.

SNOW--Continued

(6) Runoff-factors: hydrology--Continued

W. W. Horner and others, Papers on hydrologic investigations at Washington University, Civ. Eng., v. 10, pp. 230-235, 303-306, 1940.

W. W. Horner and S. W. Jens, Surface runoff determination from rainfall without using coefficients, Proc. Amer. Soc. Civ. Eng., v. 67, pp. 533-568, 1941.

R. E. Horton, The infiltration-theory of surface-runoff, Trans. Amer. Geophys. Union, Part II, p. 541, 1940.

W. G. Hoyt, Committee on Runoff, 1939-40, Trans. Amer. Geophys. Union, Part II, pp. 373-374, 1940.

W. G. Hoyt, Current technique in rainfall-runoff analysis, Proc. Hydraulics Conf., Iowa City, Iowa, 1940, Univ. Iowa Studies, Bull. No. 20, pp. 92-102, 1940.

Hydrologic Studies: Compilation of rainfall and run-off from the watersheds and terraced areas of the Fort Hays Conservation Experiment Station, Hays Station, Hays, Kansas, 1930-38, Mimeo., U. S. Dept. Agric., Soil Conserv. Serv., Tech. Pub. 37, 1940.

Influence of vegetation and watershed treatments on run-off, silting, and stream flow: A progress report of research, prepared by For. Serv. and Soil Conserv. Serv., U. S. Dept. Agric., Misc. Pub. No. 397, 1940.

G. S. Knapp, Water resources of the mid-continent area, Civ. Eng., v. 10, pp. 652-655, 1940, discussion, v. 11, pp. 45-46, 1941.

H. C. Knoblauch and J. L. Haynes, The effect of contour-cultivation on runoff, Trans. Amer. Geophys. Union, Part II, pp. 499-504, 1940.

J. M. Little, Erosional land-slope-profile shape in terms of the erosive power of rainfall-runoff, Trans. Amer. Geophys. Union, Part II, pp. 499-504, 1940.

W. W. McLaughlin, Factors affecting run-off forecasts based on snow surveys, Soil Conserv., v. 5, No. 6, pp. 148-151+, 1939.

P. Pokrofsky, On the maximum discharge from small watersheds in Karstov Chusovskoy region of the Sverdlovsk district, Met. i Hydro., v. 11, p. 102, 1940 (in Russian).

P. V. Pokrovsky, On the organization of the study of maximum run-off from small water sheds, Met. i Hydro., v. 8, p. 88, 1940 (in Russian).

B. V. Poliakov, Calculation of maximal discharge in small watersheds, Met. i Hydro., v. 3, p. 54, 1940 (in Russian).

Rain simulator studies of the effect of slope on erosion and run-off, 1938 (a preliminary report of the Northwest Appalachian Soil and Water Conservation Experiment Station, Zanesville, Ohio), Mimeo., U. S. Dept. Agric., Soil Conserv. Serv., Tech. Pub. 36, 1940.

A. I. Reshetnikov, On the problem of the effect of agrotechnical measures upon the superficial run-off under the conditions of the Valdai Hydrological Station, Met. i. Hydro., No. 9, pp. 73-79, 1940 (in Russian).

H. S. Riesbol, Technique of hydrologic research, Agric. Eng., v. 21, pp. 269-273, 1940.

Run-off and soil losses from critical storms occurring in the upper Mississippi Valley, Soil Conserv. Exp. Station, La Crosse, Wisc., Mimeo., September 1940.

S. I. Rybkin, An attempt of statistical control of the computations of run-off regulations over many years, Met. i Hydro., No. 11, pp. 73-84, 1940.

R. Saito, On the mechanism of thaw water movement in snow deposit, J. Met. Soc. Japan, second series, v. 19, No. 4, p. 14, 1941.

D. I. Shasko, Dependence of the rate of transpiration from different soil moisture and from soil type, Met. i Hydro., v. 11, p. 89, 1940 (in Russian).

L. K. Sherman, The hydraulics of surface runoff, Civ. Eng., v. 10, No. 3, pp. 165-166, 1940.

A. M. Shulgin, On temperature régime and moisture of the upper sub-surfaced agrocultivated layers, Met. i Hydro., v. 5-6, p. 92, 1940 (in Russian).

D. L. Sokolovsky, On formula of maximal flow of thawing waters in relation to the solar radiation and temperature of the air, Met. i Hydro., No. 3, pp. 68-72, Moscow, 1939.

A. R. Sotchenko, On the computation of run-off under the conditions of the river bed blocking, Met. i Hydro., v. 7, p. 43, 1940 (in Russian).

J. N. Spaeth and C. H. Diebold, Some interrelationships between soil characteristics, water tables, soil temperature, and snow-cover in the forest and adjacent open areas in south-central New York, Cornell Univ. Agric. Exp. Sta. Memoir 213, 74 pp., 1938.

Stafford C. Happ, G. Rittenhouse, G. C. Dobson, Some principles of accelerated stream and valley sedimentation, U. S. Dept. Agric., Tech. Bull. No. 695, 133 pp., 1940.

Study of run-off, U. S. Dept. Agric., Soil Conserv., p. 297, May 1941.

U. S. Dept. Agric., Influences of vegetation and watershed treatments on runoff, silting, and stream flow, Misc. Pub. 397, 80 pp., 1940.

G. R. Williams and others, Natural water loss in selected drainage basins, U. S. Dept. Int., Geol. Surv. W.-S. Paper 846, 59 pp., 1940.

SNOW--Continued

(6) Runoff-factors: hydrology--Concluded

W. Wundt, Beiträge zur Temperatur der fliessenden Bewässer, Petermanns Geograph. Mitteil., 86. Jahrg. 12. Heft, pp. 399-406, 1940.

Z. Yosida, A method for determining the thaw water content in a snow layer, J. Met. Soc. Japan, second series, v. 18, No. 10, p. 35, 1940.

V. V. Zeeberg, Comparative influence of rains and thawing snow on the whole amount of solid discharge of the rivers in the European part of USSR, Met. i Hydro., No. 3, pp. 75-86, Moscow, 1940 (in Russian).

(7) Floods

J. K. Bartlett and T. G. Pfiffner, Probable maximum flood flow from a small watershed, Civ. Eng., v. 10, pp. 233-235, 1940.

J. L. Benson, H. A. Foster, and E. E. Foster, Maximum probable floods on Pennsylvania streams discussion, Proc. Amer. Soc. Civ. Eng., v. 66, No. 10, pp. 1849-1857, 1940.

C. F. Brooks and A. H. Thiessen, The meteorology of great floods in the eastern United States, Smithsonian Rep., Pub. 3506, pp. 325-348, 1938.

J. E. Church, The relation of snow to maximum flood-peaks: A discussion, Trans. Amer. Geophys. Union, Part III, pp. 953-968, 1940.

W. P. Creager, Possible and probable future floods: Analysis of data suggests need for research in storm probabilities, Civ. Eng., v. 9, pp. 668-670, 1939; discussion, v. 10, pp. 111-113, 1940.

E. B. Debler, Multiple-use aspects of irrigation projects, Civ. Eng., v. 11, pp. 83-86, 1941.

Z. V. Dejorjio, Snowy and glacial floods on the rivers of the Central Asia, Met. i Hydro., No. 3, pp. 68-74, Moscow, 1940 (in Russian).

E. H. Fletcher, Floods in the Sacramento Valley, February 27, March 6, 1940, Mon. Weath. Rev., Washington, pp. 71-74, March 1940.

E. H. Fletcher, Melting snow as a flood factor in the Sierra Nevada, Bull. Amer. Met. Soc., v. 21, No. 2, pp. 59-63, 1940.

Flood protection data: Progress report of the committee, Proc. Amer. Soc. Civ. Eng., v. 66, pp. 615-626 (bibliog., pp. 620-623), 1940; discussion, v. 66, pp. 1225-1228, 1347-1348, and 1723-1825, 1940.

A. S. Fry, Transmit river stages with radio gages, Elec. W., v. 114, pp. 1166-1167, 1940.

House flood control bill includes $191,000,000 for dams and local works, Eng. News-Rec., v. 125, pp. 613-617, 1940.

Hydrology of Virginia, Part 2, Flood studies: Storms that have caused great floods; great rainfalls, Eng. Exp. Sta. Series No. 43, Va. Polytech. Inst., Blacksburg, Va., 1940.

C. S. Jarvis, Maximum probable floods on Pennsylvania streams: Discussion, Proc. Amer. Soc. Civ. Eng., v. 67, No. 1, pp. 137-140, 1941.

N. R. Laden, T. L. Reilly, and J. S. Minnotte, Synthetic unit-hydrographs, distribution-graphs, and flood-routing in the upper Ohio River Basin, Trans. Amer. Geophys. Union, Part II, pp. 649-660, 1940.

H. B. Lynch, Transient flood peaks, Proc. Amer. Soc. Civ. Eng., v. 65, pp. 1605-1624, 1939; discussions, v. 66, pp. 176-178, 546-552, 745-769, 995-1002, 1104-1108, 1337-1338, and 1665-1670, 1940.

C. McDonough, Grouped reservoirs control floods on the Colorado River, Eng. News-Rec., v. 124, pp. 793-796, 1940.

H. D. McGlashan and R. C. Briggs, Floods of December 1937 in northern California, U. S. Geol. Surv. W.-S. Paper 843, pp. 1-497, 1939.

J. W. Mangen, Flood-forecasting service in Pennsylvania, J. Amer. W.-W. Assoc., v. 33, No. 2, pp. 213-218, 1941.

John Martin reservoir project for flood control and water conservation in the Great Plains area, Eng. News-Rec., v. 125, pp. 614-617, 1940.

P. A. Nezhikhovski, Method of short-period forecasts of spring floods, Met. i Hydro., No. 12, pp. 56-62, 1940 (in Russian).

T. Nomitu, Studies on flood prediction in Japan, Jap. J. Astr. Geophys., v. 17, No. 1, pp. 83-100.

W. J. Parsons, Jr., The relation of snow to maximum flood-peaks, Trans. Amer. Geophys. Union, Part III, pp. 951-953, 1940.

C. J. Posey and Fu-Te I., Functional design of flood control reservoirs, Proc. Amer. Soc. Civ. Eng., v. 65, pp. 1317-1326, 1939; discussion, v. 65, pp. 1765-1766, v. 66, pp. 507-516, pp. 695-706, pp. 961-963, 1939, 1940.

H. W. Richardson, River development and control, 1940, Eng. News-Rec., v. 126, pp. 236-238, 1941.

SNOW--Continued

(7) Floods--Concluded

C. F. Ruff, Maximum probable floods on Pennsylvania streams, Proc. Amer. Soc. Civ. Eng., v. 66, No. 7, pp. 1239-1276, 1940.

Sacramento river experiences its greatest flood, Eng. News-Rec., pp. 124-341, 1940.

F. F. Snyder, Predicting headwater river-stages directly from rainfall, Trans. Amer. Geophys. Union, Part II, pp. 485-490, 1940.

J. C. Stevens, Winter overflow from ice-gorging on shallow streams, Trans. Amer. Geophys. Union, Part III, pp. 973-979, 1940.

G. R. Williams and L. C. Crawford, Maximum discharges at stream-measurements stations through December 31, 1937, with a supplement including additions and changes through September 30, 1938, by W. S. Eisenlohr, Jr., U. S. Geol. Surv. W.-S. Paper 847, pp. 1-272, 1940.

J. A. Worster, Rational method of determining maximum runoff, Farming in S. Africa, v. 15, pp. 299-303, 1940.

(8) Conservation

W. H. Collet and H. G. Wilm, The influence of a lodgepole-pine forest on storage and melting of snow, Trans. Amer. Geophys. Union, Part II, pp. 505-508, 1940.

A. Dubach, The improved flow of the rivers of the Caspian basin due to afforestation in the North and North-West, Met. i Hydro., v. 7, p. 80, 1940.

J. Kittredge, and others, Interception and stemflow in a pine plantation, J. For., v. 39, No. 6, pp. 505-522, 1941.

J. Kittredge, Jr., The magnitude and regional distribution of water losses influenced by vegetation, J. For., v. 36, No. 8, pp. 775-778, 1938.

G. D. Matthews, Snow utilization in prairie agriculture, Canada Agric. Pub. 696, 21 pp., 1940.

V. G. Nesterov, To the question about influence of forest on the snow cover, Met. i Hydro., v. 3, p. 136, 1940.

Th. N. Russanov, The snowfall as a factor limiting the expansion of the desert vegetation, Bull. de l'Univ. de l'Asie Centrale, Libraison 22, pp. 375-379, 1938 (in Russian with English summary, p. 379).

Saving snow: Plowed into rows, it prevents later drifting, Sci. Amer., v. 163, p. 333, 1940.

J. N. Spaeth and C. H. Diebold, Some interrelationships between soil characteristics, water tables, soil temperature, and snow-cover in the forest and adjacent open areas in south-central New York, Cornell Univ. Agric. Exp. Sta., June 1938.

(9) Snow-removal

V. J. Brown, Snow types encountered in highway snow removal: Prairies and mountains of Washington, Roads and Streets, v. 83, pp. 45-47, September 1940.

Chasing a snowstorm: Reading, Massachusetts, reports snow conditions and use of equipment in seven major storms, Amer. City, v. 55, pp. 47-48, September 1940.

County organization for winter road maintenance, Can. Eng. Roads and Bridges, v. 78, p. 33, October 1940.

R. C. Elder, Clearing snow from the nation's backbone: Trail Ridge Road in Colorado's Rocky Mountain National Park, Comp. Air M., v. 45, pp. 6219-6221, 1940.

M. E. Evans, Safe streets throughout the year: Cleveland keeps its streets clear of ice and snow, Amer. City, v. 55, pp. 56-57, November 1940.

E. A. Finney, Snow drift control by highway design; result of wind tunnel investigations, Roads and Streets, v. 83, pp. 45-48, 1940; abstract, Pub. Works, v. 71, pp. 29-30, 1940.

J. S. Flockhart, Snow and ice removal with rock salt in Newark, N. J., Pub. Works, v. 71, pp. 11-12, September 1940.

Hesperus II: Wrecker-snow-plow-tow-car built by United electric railways, Providence Bus Transportation, v. 19, pp. 380-381, 1940.

W. B. Hutcheson, Winter maintenance of northern roads, Can. Eng. Roads and Bridges, v. 78, pp. 34-35, October 1940.

L. B. MacMillan, Winter roads in Prince Edward Island, Can. Eng. Roads and Bridges, v. 79, p. 23, 1941.

J. D. MacVicar, Snow-types met in highway snow-removal, Trans. Amer. Geophys. Union, Part III, pp. 932-935, 1940.

T. A. McNeill, Winter problems on divided highways: Queen Elizabeth Way, Can. Eng. Roads and Bridges, v. 78, p. 36, October 1940.

I. C. Marritt, Tree planting to stop snow drifting on roads, Farmer's Advocate, v. 75, p. 324, 1940.

M. Kuroda and K. Kinosita, Wind-tunnel experiments on snow fences, Bull. Inst. Phys. Chem. Res., v. 19, No. 8, pp. 1175-1191, 1940.

Niagara rotary snow-plow, Can. Eng. Roads and Bridges, v. 79, p. 53, June 1941.

SNOW--Continued

(9) Snow-removal--Concluded

Organization and proper equipment, Can. Eng. Roads and Bridges, v. 78, p. 28, October 1940.

Organization and salt fight winter hazards, Buffalo, N. Y., Amer. City, v. 56, p. 11, March 1941.

Organization, methods, equipment, and materials for snow and ice control, Pub. Works, v. 71, pp. 25-28, 30-31, October 1940.

H. W. Perry, Out-blitzing the blizzard, Chris. Sci. Mon. Mag., p. 6, March 1, 1941.

Round-table conference: Snow and ice removal from sidewalks, Can. Eng. Roads and Bridges, v. 79, p. 90, February 1941.

H. A. Scribner, Winter always comes, Aviation, v. 40, pp. 59-60, March 1941.

Sicard snow blower, Can. Eng. Roads and Bridges, v. 79, p. 90, February 1941.

Snow burning machine clears airport runways, Eng. News-Rec., p. 13, February 6, 1941.

Snow control dependent upon summer maintenance: Oregon building new maintenance headquarters, Roads and Streets, v. 83, pp. 33-35, September 1940.

Town snow-plowing of private drives illegal in New York State, Amer. City, v. 56, p. 11, January 1941.

C. M. Upham, Winter maintenance: Abstract, Can. Eng. Roads and Bridges, v. 78, pp. 67-68, November 1940.

Winter roads increase volume of traffic; effect on gasoline consumption, Can. Eng. Roads and Bridges, v. 78, p. 29, October 1940.

(10) Transport, winter sports, avalanches

Aurora borealis over Michigan; snow and ice carnival sponsored by the Marquette winter sports club, Recreation, v. 34, pp. 607-608, 1941.

E. L. Chicanot, Canadian Switzerland: Laurentia area, Comp. Air Mag., v. 45, pp. 6302, 6363-6366, 1940.

J. F. Coggswell, Poor man's snow heaven: New Hampshire sells snow and fun at bargain prices, Sat. Eve. Post, v. 213, pp. 18-19, March 15, 1941.

J. C. Crouch, Ski-etiquette and ski-safety, Trans. Amer. Geophys. Union, Part III, pp. 925-928, 1940.

Dartmouth's 31st annual winter carnival, Newsweek, v. 17, p. 54, February 17, 1941.

T. E. Dever, Ski course for Colorado resort: Glenwood Springs, Amer. City, v. 56, p. 87, February 1941.

F. Elkins, Complete ski guide, Doubleday,Doran, New York, 1940, 286 pp.

H. Erickson, Winter activities in Minneapolis, Recreation, v. 34, p. 553, 1940.

Chet Errett, Across the Yosemite Sierra on skis, Sierra Club Bull., v. 26, No. 1, pp. 141-142, 1941.

P. Gerhard, Ski research, Mt. Wash. Obs. News Bull., No. 8, pp. 2-3, 1941.

A. G. Goff and G. F. Otten, Experimental determination of impact forces of avalanches, Izv. An SSSR, Ser. Geogr. i Geofiz., No. 3, pp. 303-308, 1939.

B. Griffiths, Skiing for Wisconsin youth, Recreation, v. 34, pp. 537, 538, 569, 1940.

W. C. Heinz, Home-maid ski champ, Collier's, v. 107, p. 22, March 1, 1941.

E. Hess, Le travail de la Commission suisse pour l'étude de la neige et des avalanches, J. For. Suisse, v. 91, pp. 93-100, 117-127, 1940.

A. C. Hicks, Taking winter on a holiday, Travel, v. 76, pp. 12-15, January 1941.

H. Hoek, Begegnungen mit der Lawine, Die Alpen, No. 1, pp. 1-12, 1941.

A. Holmes, Putting your skis in shape, Pop. Sci., v. 138, pp. 182-183, 1941.

H. L. Jackson, Skiing goes native, Collier's, v. 107, p. 17, January 18, 1941.

E. Jessup, Teach your child to ski, Parents Mag., v. 16, p. 23, February 1941.

G. Keene, How to ski standing up, Chris. Sci. Mon. Mag., pp. 8-9, December 14, 1940.

G. Keene, Spring skiing in Tuckerman, Chris. Sci. Mon. Mag., p. 11, March 22, 1941.

B. Knox, Ski upset, Collier's, v. 107, p. 48, 1941

L. Koegel, Schnee und Lawinen, Geogr. Zs., v. 46, p. 132, 1940.

W. Kohnke, Gross-Schneefälle in Deutschland, insbesondere die Schneebruchkatastrophe vom 16 April 1936, Met. Zs., v. 56, pp. 418-428, 1939; abstract, p. 418.

Lawinen: Die Gefahr für den Skifahrer, Ratschläge zur Beurteilung der Gefahr und Bekämpfung von Unfällen, bearbeitet von der Schweiz, Schnee- und Lawinenforschung und dem Parsenndienst, copyright by Aschmann and Scheller AC., Zürich, Switz., 114 pp., 1940.

E. F. Loosli, F. A. Sutcliffe, Skiing in the province of Quebec, J. Can. Geog., v. 21, pp. 268-279, 1940.

S. N. Matveew, Sur une onde d'air, provoquée par les avalanches, Problemy Fisicheskoi Geografii, V. 9, p. 89, 1940.

B. Meredith, Enchantment on snow, Arts and Dec., v. 53, pp. 12-15, December 1940.

SNOW--Concluded

(10) Transport, winter sports, avalanches--Concluded

W. Naegler, Grosser Schneefall und Schneebruch im Dezember 1939, Zs. a. Met., v. 57, pp. 30-31, 1940.

New Hampshire winter map, 1940-1941 season, State Planning and Development Comm., Concord, N. H.

J. Nordlinger, Middle West where skiers are born and made, Chris. Sci. Mon. Mag., p. 14, December 28, 1940.

North of Boston and north of Montreal, New Yorker, v. 16, pp. 61-63, January 18, 1941.

Now that winter's here! hiking and snowshoeing, Recreation, v. 34, pp. 523-525, 1940.

A. P. Pavlov, Meteorologic conditions for the forecasting of avalanches in the Khibins, Doklady Akad. Nauk SSSR (Papers Acad. Sci. USSR), New series, T. 24, No. 3, pp. 290-293, 1939 (in Russian).

Planning a winter sports area, Lexington, Mass. plan, Recreation, v. 34, p. 554, 1940.

F. Prohaska, Neuere Schnee- und Lawinenforschungen in der Schweiz, Met. Zs., v. 57, p. 249, 1940.

Promise of biggest season in nation, Newsweek, v. 16, p. 40, December 23, 1940.

Promoting new passenger business; service for skiers, Can. Pac. Ry. Age, v. 109, p. 987, 1940.

J. K. Reid, Winter sports in California's southland, Recreation, v. 34, pp. 549-550, 1940.

Rocketing on skis; rapid-action photographs, N. Y. Times Mag., p. 17, February 2, 1941.

F. Roten, Compte rendu du cours sur les avalanches, donné aux functionnaires forestiers suisses du 15 au 21 décembre 1940, J. For. Suisse, v. 92, pp. 40-43, 55-61, 1941.

Safety for skiers, Recreation, v. 34, p. 536, 1940.

A. Samokhin, Concerning the snow avalanche in the Kasarsk Canyon, Pogoda (Weather), No. 6, pp. 15-16, July 1940.

Sierra Club Bulletin, v. 26, No. 1, 1941, Skis to the fourteen-thousanders.

Ski hosteling, Parents Mag., v. 16, p. 100, February 1941.

Skiing accidents are prevented by simple pre-season exercises, Life, v. 9, pp. 55-56, December 9, 1940.

H. Slocum, Sitzmarks in Minneapolis; ski classes and clubs, Recreation, v. 34, pp. 601-602, 1941.

C. G. Suits, Mechanics of skiing, Sci. Dig., v. 9, pp. 56-58, May 1941.

Swiss snow and avalanche research, Weissfluhjoch (Contents of the 16-mm film of the work of the Swiss Commission for Snow and Avalanche Research in the Parsenn region, Weissfluhjoch, 2660 meters above sea-level, winter 1936-37), Zürich, 1939, 2 mimeo. leaves.

Tokle shows top ski-jumping form: Magic eye shots of champion, Life, v. 10, p. 58, February 24, 1941.

Torger Tokle leaps to fame in America on soaring skis, Newsweek, v. 17, p. 40, January 27, 1941.

Uncle Sam on skis, House Building, v. 83, pp. 86-87, 1941.

E. R. Valentine, Compleat ski-er, N. Y. Times Mag., p. 11, March 2, 1941.

White art of skiing, Recreation, v. 34, pp. 527-529, 1940.

Winter fun for all, Recreation, v. 34, pp. 541-543, 1940.

Winter sports in Barre, Recreation, v. 34, pp. 568-569, 1940.

Winter sports for Michigan, Recreation, v. 34, p. 540, 1940.

Yumper, Torger Tokle, Time, v. 7, p. 72, February 24, 1941.

ICE

(1) General

D. L. Arenberg, The formation of small hail and snow pellets, Bull. Amer. Met. Soc., v. 22, pp. 113-116, 1941.

D. L. Arenberg and P. J. Harney, The Mount Washington icing research program, Bull. Amer. Met. Soc., v. 22, pp. 61-63, 1941.

E. Bade, Sheathed in ice: How to save affected trees, House and Gardens, v. 79, Supp. 43, January 1941.

K. Bender, Die Früjahrfröste an der Unterelbe und ihre Bekämpfung (The spring frosts in the lower Elbe and the fight against them), Zs. Ang. Met. Das Wetter, Heft 9, pp. 273-288, 1939.

M. N. Bianki, On the question of the definition of the concepts of white frost, frost, solid flight, and slippery ice (Glatteis), Problemy Arktiki, No. 7-8, pp. 118-123, 1939.

V. A. Blagoveshchenki, On long-range forecast of frost in southern districts, Priroda, No. 6, pp. 58-61, 1939.

V. A. Bobkov, Method of theoretical computation of the duration of water freezing in the open, Met. i Hydro., No. 8, pp. 52-59, 1940 (in Russian).

Sir W. Bragg, Ice, Proc. Inst. Gr. Brit., v. 30, No. 14, pp. 283-301, 1938.

ICE--Continued

(1) General--Concluded

C. J. Cave, The ice storm of January 27-29, 1940, Aeronaut. J., v. 66, No. 285, pp. 143-151, 1940.

G. B. Chizhov, To the question of over-cooling and crystallization of water under various conditions, Met. i Hydro., No. 4, pp. 11-18, 1940 (in Russian).

R. P. Coffin, Harvest of diamonds: Ice harvest along the Kennebec in the nineties, Chris. Sci. Mon. Mag., p. 3, February 21, 1941.

B. Danilov, Gidrologiia so l'da (hydrology with ice), Leningrad, Glavsevmorpieti, 1939, 50 pp. with illustrations (in Russian).

C. E. Frankcom, Ice conditions in the Baltic and Danube areas, December 1, 1939 to January 23, 1940, Met. Mag., v. 75, No. 889, pp. 1-8, 1940.

Gakkel and Laktionov, Albom ledovykh obrazovanii (An album of ice formations), pub. by North Sea Route Commission, Moscow, 1940, 47 pp.

B. S. Gapomov, Limits of temperature to the formation of slippery ice and white frost from supercooled fog, Izv. An SSSR, Ser. Geogr. i geofiz., No. 2, pp. 205-216, 1939.

Glazed frost, January, 1940, Met. Mag., v. 75, No. 889, pp. 12-13, 1940.

The glazed frost of January 1940, Met. Mag., v. 75, No. 890, pp. 21-25, 1940.

P. Götz, Saharasand im Rauhreif, Zs. angew. Met., 1940.

S. Ikeda, The structure of the silver-thaw and its temperature, J. Met. Soc. Japan, second series, v. 19, No. 5, p. 20, 1941.

S. P. Kachurin, Abrasion and perpetual icing in the Anadyr, Izv. Gos. Geogr. Obsch., v. 71, No. 7, pp. 1005-1019, 1939.

N. K. Karasev, Study of frost damage causing soil bulging injuring the root system of plants, Met. i Hydro., No. 12, pp. 63-69, 1940 (in Russian).

A. Khrgian, Physical foundations for the fight against snow on railways, Trudy Moskovskovo Met. Inst., No. 1, pp. 145-151, 1939 (in Russian).

M. M. Korunov, Intensity of the formation of ice layer from the water poured on the ice, Met. i Hydro., No. 12, pp. 92-94, 1940 (in Russian).

K. O. Lange, Vereisungsmessungen mit der Harvard-Radiosonde (measures of icing with the Harvard radiosonde), Beiträge Phys. fr. Atmos., Bd. 25, Heft 4, 1939.

H. Landsberg, The use of solar energy for the melting of ice, Bull. Amer. Met. Soc., v. 21, No. 3, pp. 102-107, 1940.

H. Oellrich, Die Eisverhältnisse des Winters 1938/39 in den ausserdeutschen europäischen Gewässern, Verfahren. Ann. Hydr. Mar. Met., Heft 1, pp. 17-24, 1940.

V. N. Pyatnitski, Causes of the formation of "naledi" (layers of frozen mud and water forced out of ice bulges) and methods of controlling them, Met. i Hydro., No. 9, pp. 61-67, 1940.

A. N. Rakhimanov and M. Ya Krukovski, Experimental investigation of continuous vection under the ice cover in the lower zone of the Nizhnesvir settlement, Izvestia Nauchno-Issledovatelskovo Inst. Hydrotekhniki, v. 25, pp. 5-22, 1939 (in Russian).

G. O. Riabukhin, On some signs of perpetual icing in the district of Ust-Port, Problemy Arktiki, No. 6, pp. 82-85, 1939 (in Russian).

H. K. Rouse, An ice storm in Texas, U. S. Dept. Agric., Soil Conserv., pp. 241-244, 1941.

G. Seligman, Photographs of rime, Quart. J., v. 66, No. 285, p. 214, 1940.

A. N. Silbermann, On the process of underwater ice formation in flowing reservoirs, Met. i Hydro., v. 12, p. 3, 1940.

M. Sumgin, On Comrade Khrgian's note "Today's knowledge of perpetual icing", Met. i Hydro., No. 4, pp. 123-124, 1940 (in Russian).

E. Wall and E. Huss, Einige merkwürdige Kristallisations-Erscheinungen des Eises, Wetter, v. 57, p. 84, 1940.

B. P. Weinberg, Lyod. Svoistva, vozniknovenie i ischeznoveniye (Ice, nature, origin, and disappearance), Leningrad, 1940, 517 pp.

R. Wright, Ice storm, House and Garden, v. 78, pp. 16-17, December 1940.

(2) Sea and river ice

V. I. Arnold-Alyabiev, On the duration of ice in the Barentz and Kara Seas, Problemy Arktiki (Problems of the Arctic), No. 6, pp. 21-30, 1939 (in Russian).

H. A. Belinskii, To improve ice observations, Pogoda (Weather), No. 6, pp. 15-16, July 1940 (in Russian).

V. A. Bobkov, Method of theoretical computation of the duration of water freezing in the open, Met. i Hydro., v. 8, p. 52, 1940.

V. G. Bogorov, Peculiarities in the seasonal phenomena of the arctic seas and their meaning for ice purpose, Zoologicheski Zhurnal, v. 18, No. 5, pp. 735-747, 1939.

A. Burke, Morskie l'dy (sea icebergs), pub. by North Sea Route Commission, Moscow, 1940, 95 pp.

ICE--Continued

(2) Sea and river ice--Concluded

N. Chernigovski, On the lye reserve of the sea ice in the Boris-Vilkitski strait, Problemy Arktiki, No. 7-8, pp. 123-125, 1939.

H. Corder, The freezing of a tidal river, Met. Mag., v. 75, No. 891, p. 55, 1940.

C. E. Frankcom, Ice conditions in the Baltic and Danube areas, December 1, 1939, to January 23, 1940, Met. Mag., v. 75, No. 889, pp. 1-7, 1940.

D. B. Karelin, Thawing of the ice in the Arctic under the influence of air temperature, Met. i Hydro, No. 4, pp. 71-75, 1940 (in Russian).

E. L. Kelting, The freezing of a tidal river, Met. Mag., v. 75, No. 893, pp. 81-86, 1940.

Z. v. Keőpeczi-Nagy, Die Eisverhältnisse der Flüsse in Ungarn im Winter 1939/40, Az Időjárás, v. 44, p. 102, 1940.

E. A. Kondratieva, Selection and analysis of temperatures forecasting the ice formation for the rivers in the North, Met. i Hydro., v. 3, p. 62, 1940.

V. V. Lebedev, New formulas for the growth of ice in arctic rivers and seas, Met. i Hydro., No. 8, pp. 40-51, 1940 (in Russian).

A. Lende, Sea-ice conditions at the coast of Latvia during the winter 1938-39, Latvia, Marine Dept., Hydrog. Sect., Riga, 1939.

W. S. Nasarow, Heutiger Stand der Eisprognosen, Met. i Hydro., No. 1, pp. 52-63, 1938; reviewed in Ann. Hydr., Heft 1, p. 37, 1940.

C. J. Östman, On sambandet mellan isläggningen vid svenska ostkusten och meteorologiska faktoren (On the relation between ice formation on the Swedish east coast and meteorologic factors), Meddelanden från Statens Meteorologisk-Hydrografisk Anstalt, Bd. 7, No. 5, 16 pp., 1939 (in Swedish).

W. J. Parsons, Jr., Ice in the northern streams of the United States, Trans. Amer. Geophys. Union, 1940, Part III, pp. 970-973, 1940.

B. L. Samoilov, The ice on the Don at the beginning of April, Vodosnabzhenie i sanitarnaya tekhnika, No. 10-11, pp. 39-41, 1939.

I. I. Schell, Foreshadowing the severity of the iceberg season south of Newfoundland, Bull. Amer. Met. Soc., pp. 7-10, January 1940.

A. E. Schmidt, Schiffahrt und Eisgefahr, Hansa, p. 45, 1939.

A. N. Silbermann, On the process of underwater ice formation in flowing reservoirs, Met. i Hydro., No. 12, pp. 3-16, 1940 (in Russian).

B. A. Skopintsev, Winter hydro-chemical régime of the river Volga under ice for the period between 1908 and 1939, Met. i Hydro., No. 5-6, pp. 62-70, 1940 (in Russian).

E. H. Smith, Recent movements of North Atlantic ice and a proposed Coast Guard expedition to the west Greenland glaciers, Trans. Amer. Geophys. Union, Part II, pp. 668-672, 1940.

M. M. Somov, On the question of the average thickness of the ice on inland seas, Problemy Arktiki, No. 6, pp. 11-20, 1939 (in Russian).

F. M. Soule and G. van A. Graves, International ice observation and ice patrol service in the North Atlantic Ocean, Bull. U. S. Coast Guard, No. 28, season of 1938, Washington, 1940, 173 pp.

V. L. Tsurikov, On the growth of sea ice, Severny Morskoi Put (Travel in the northern seas), v. 14, pp. 38-53, 1939 (in Russian).

B. P. Weinberg and S. M. Andreev, Limit of plasticity of river ice, Trudy Sibirskovo Fisiko-Tekhnicheskovo Instituta, v. 5, No. 3, pp. 15-31, 1939 (in Russian).

N. N. Yagodin, Some ice obstacles in the Dneproges Lenin and measures for their removal (Investigations of the winter 1936-37), Izv. Nauchno-Issledovatelskovo Instituta Gidrotekhniki, v. 24, pp. 90-110, 1939 (in Russian).

Ya Ya Gakkel, Determination of the amount of ice (on the sea area under observation), Problemy Arktiki, No. 7-8, pp. 81-88, 1939.

S. Yoshimura, The freezing of Japanese lakes, Jap. J. Astr. Geophys., v. 17, No. 1, pp. 157-160.

N. N. Zubov, On the cruise of the ice-breaker Sadko (September 1, 1938 - February 1, 1939) [Contribution to the study of the question of ice and water marks in the polar basin], Severny Morskoi Put (Travel in the Northern seas), v. 14, pp. 5-17, 1939 (in Russian).

N. N. Zubov, On the index of icing of the sea, Problemy Arktiki, No. 4, pp. 5-12, 1939 (in Russian).

(3) Glaciers

H. W. Ahlmann and Th. Lindblad, Die Grössenveränderungen des Kårsajökels in Schwedisch-Lappland während der Jahre 1909-1939, Geograf. Ann., Arg. 22, Heft 1-2, pp. 80-94, 1940.

H. W. Ahlmann, The Styggedal glacier in Jotunheim, Norway: Its regime, its variations in size and their climatological causes, and some general remarks on these, Geograf. Ann., Arg. 22, Heft 3-4, pp. 95-130, 1940.

V. K. Altberg, An attempt of the determination of the glacier's thickness by means of sound method, Met. i Hydro., v. 12, p. 72, 1940 (in Russian).

ICE--Continued

(3) Glaciers--Continued

H. Baulig, Sur les "Gradins de Piedmont," J. Geomorph., v. 2, No. 4, pp. 281-304, 1939 (English summary, p. 298-304).

A. J. Bull, Cold conditions and land forms in the South Downs, Proc. Geol. Assoc., v. 51, Part 1, pp. 63-71, 1940.

R. G. Carruthers, Discussion on papers published in previous volumes of the Quarterly Journal: On northern glacial drifts: Some peculiarities and their significance, v. 95, pp. 299-330, 1939. Q. J. Geol. Soc. London, v. 96, Part 2, pp. 249-269, 1940.

R. T. Chamberlin, Glacier mechanics, Amer. Alpine J., v. 4, No. 1, pp. 40-53, 1940.

V. Conrad, The Vatnajökull glacier (preliminary report on the work of the Swedish-Icelandic investigations 1936-1937), reviewed from the article by H. W. Ahlmann and S. Thorarinsson, Geog. Rev., v. 28, No. 3, pp. 412-438, 1938, in Bull. Amer. Met. Soc., v. 21, No. 6, p. 275, 1940.

W. S. Cooper, A fourth expedition to Glacier Bay, Alaska, Ecology, v. 20, No. 2, pp. 130-155, 1939.

C. A. Cotton, Glacier motion: A review of theories, N. Z. J. Sci. Tech., v. 21, No. 6B, pp. 281-286, 1940.

C. A. Cotton, Taylor's hypothesis of headward glacial erosion, J. Geomorph., v. 3, No. 4, pp. 346-352, 1940; discussion of Griffith Taylor's hypothesis.

M. Demorest, The rock called ice, Trans. N. Y. Acad. Sci., Ser. 2, v. 3, No. 2, pp. 25-28, 1940.

E. Dittmer, Zur Vergreitung altinterglazialer Meeresablagerungen in Nordfriesland, Westküste, Jahrg. 2, Heft 1, pp. 39-115, 1939.

J. L. Dyson, Recession of glaciers in Glacier National Park, Montana, Trans. Amer. Geophys. Union, Part II, pp. 508-510, 1940.

R. F. Flint, End moraines of ice sheets, Zs. Gletscherkunde, Bd. 27, Heft 1-2, pp. 88-97, 1940.

M. M. Fradkin, On the two fold glaciation of the West Siberian lowland, C.-R. l'Akad. Sci. de l'URSS, N.S., v. 24, No. 4, pp. 347-348, 1939.

I. P. Gerasimov and K. K. Markov, The glacial period in the territory of the USSR, Moscow, 1939, 462 pp., Russia, Acad. Sci., Trans. Inst. Geog., No. 33 (in Russian with English summary, pp. 443-462).

A. R. Glen, The glaciology of north east land, Geograf. Ann., Heft 1, 1939.

V. Gorbunov, The glaciers of the basin of Lakes Balkhash, Sasyk-kul and Ala-kul, Izv. Gos. Geogr. Obshch., v. 71, No. 6, pp. 831-843, 1939.

I. H. Grant and K. Mason, The Upper Shyok glaciers, 1939, Himalayan J., v. 12, pp. 52-63, 1940.

H. Gutersohn, Die Naturlandschaft von Zürich, Mitteil. G.-Ethnogr. Gesell. Zürich, v. 39, pp. 75-110, 1938-1939.

L. Horberg, Geomorphic problems and glacial geology of the Yellowstone Valley, Park County, Montana, J. Geog., v. 48, No. 3, pp. 275-303, 1940.

W. Jost, Gletscherschwankungen auf der Insel Disco in Westgrönland, Zs. Gletscherkunde, Bd. 27, Heft 1-2, pp. 20-28, 1940.

C. Keyes, Lowland ice-cap in the making, Pan-Amer. Geol., v. 73, No. 2, pp. 117-134, 1940.

N. Khromykh, Sur les glaciers du cours supérieur de la rivière Koultor (chaîne Kirghise), Izv. Soc. Russ de Geog., v. 70, No. 4-5, pp. 594-611, 1938 (in Russian).

L. Krasser, Über neuere Ergebnisse der alpinen Eiszeitforschung, Geograph. Zs., 45, Jahrg., 11-12 Heft, pp. 376-385, 1939.

S. T. Lee, Glacial features in the Swiss Alps (Abstract), J. Geog. Soc. China, v. 5, p. 13, 1938.

W. V. Lewis, Dirt cones on the northern margins of Vatnajökull, Iceland, J. Geomorph., v. 3, No. 1, pp. 16-26, 1940.

W. V. Lewis, The function of meltwater in cirque formation, Geog. Rev., v. 30, No. 1, pp. 64-83, 1940.

N. Lichtenecker, Die tiefstgelegenen Gletscher der Alpen (Ein morphologischer Beweis für die postglaziale Wärmezeit in den Alpen), Zs. Gletscherkunde, Bd. 27, Heft 1-2, pp. 29-35, 1940.

R. J. Lougee, Stagnation of ice in Connecticut, Science, N.S., v. 91, No. 2351, pp. 69-70, 1940.

J. C. Ludlum, Calcium carbonate deposits marginal to glaciers, Science, N.S., v. 91, pp. 544-555, 1940.

K. I. Lukashev and D. C. Panov, Methods of geological exploration of everfrozen ground for constructive purposes in railroad work, Leningrad, 1934, 33 pp., Geog.-Econ. Sci. Res. Inst., No. 3 (in Russian).

ICE--Continued

(3) Glaciers--Concluded

L. H. McCabe, Nivation and corrie erosion in west Spitsbergen, Geog. J., v. 94, No. 6, pp. 447-465, 1939.

S. A. Macauley, Two miles high on Grasshopper Glacier, Travel, v. 75, pp. 36-37, July 1940.

C. Mannerfelt, Glacial morfologiska studier i norska högfjäll, Norsk geograf. tidsskrift, Bind 8, Nr. 1-2, pp. 9-45, 1940 (English summary: Investigations on the glacial morphology of Norwegian mountain districts, pp. 46-47).

F. E. Matthes, Committee on Glaciers, 1939-1940, Trans. Amer. Geophys. Union, Part II, pp. 396-406, 1940.

P.-L. Mercanton, Les variations périodiques des glaciers des Alpes suisses, 60^e rapport 1939, Les Alpes, No. 6, 1940.

G. W. H. Norman, The southeastern limit of glacial lake Barlow-Ojibway in the Mistassini lake region, Quebec, Trans. Soc. Canada, Section 4, 3rd series, v. 33, pp. 59-65, 1939.

S. Obroutchev, Les forms orthogonales dans les régions des sous-sols perpétuellement congelés, Izv. Soc. Russe de Geog., v. 70, No. 6, pp. 737-746, 1938.

B. M. Page, Multiple alpine glaciation in the Leavenworth area, Washington, J. Geol., v. 47, No. 8, pp. 785-815, 1939.

N. Palgov, Procédés simples de mesures dans les observations sur les glaciers, Soc. Geog. l'URSS, Izv., v. 71, No. 2, pp. 421-427, 1939 (in Russian).

A. P. Pavlov, Meteorological conditions in relation to avalanches at Khibiny, C.-R. l'Acad. Sci. l'URSS, N.S., v. 24, No. 3, pp. 290-293, 1939.

R. Penndorf, Die potentiellen Äquivalenttemperaturen Islands und Mittelrusslands nach Aufstiegen aus Reykjavik und Moskau, Ann. Hydr. maritimen Met., v. 67, No. 11, pp. 523-529, 1939.

M. F. Perutz and G. Seligman, A crystallographic investigation of glacier structure and the mechanism of glacier flow, Jungfraujoch research party, 1938, Pub. No. 1; reprint Proc. R. Soc. London, Ser. A, No. 950, v. 172, pp. 335-360, 1939.

T. I. Pocock, Glacial drift and river terraces of the Hereford Wye, Zs. Gletscherkunde, Bd. 27, Heft 1-2, pp. 98-117, 1940.

V. Romanovsky, Application de la théorie convective aux terrains polygonaux, Rev. Geog. Phys. Géol. Dynam., v. 12, No. 2, pp. 315-327, 1938.

R. Speight, Ice wasting and glacier retreat in New Zealand, J. Geomorph., v. 3, No. 2, pp. 131-143, 1940.

R. Speight, Erosion and glacier retreat, N. Z. J. Sci. Tech., v. 21, No. 6B, pp. 286-288, 1940.

R. Spitaler, Die Bestrahlung der Erde durch die Sonne und die Temperaturverhältnisse in der quartären Eiszeit, Abhandl. Deutsch. Gesellsch. Wiss. Künste in Prag, Math.-Naturwiss., Abt. 3, Bd., Prag, 1940; reviewed in Ann. Hydro., Heft 11, pp. 401-402, 1940, by M. Rodewald.

R. Spitaler, Beziehungen zwischen Temperatur und Niederschlag in der Eiszeit, Met. Zs., Bd. 57, Heft 6, pp. 236-238, 1940.

R. Streiff, Über Firn und Gletscher, Die Alpen, Heft 9, pp. 321-328, 1940.

H. C. Streiff-Becker, Glarner Gletscherstudien, Glarus-Buchdruckerei Glarner Nachrichten, 1939 Sonderdruck aus Mitteilungen der Naturforschenden Gesellschaft des Kantons Glarus, Heft 6.

K. Suter, Die eiszeitliche Vergletscherung des Zentralapennings, Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich, Jahrg. 84, Heft 3 und 4, Beiblatt No. 31, 140 pp., 1939.

S. Thorarinsson, Present glacier shrinkage and eustatic changes of sea-level, Geograf. Ann., Arg. 22, Heft 3-4, pp. 131-159, 1940.

H. Tollner, Beiträge zur Formenkunde der arktischen Gletscheroberfläche, II Jahresbericht des Archivs für Polarforschung im Natur-historischen Museum in Wien, pp. 4-43, 1939.

L. Vardaniantz, Sur la glaciation ancienne de l'Altai et du Caucase, Izv. Soc. Russe Geog., v. 70, No. 3, pp. 366-386, 1939 (in Russian).

B. P. Vasilkov, Material to the question of the limits of the Russian glacier in the autonomous republic of Mari, Izv. Gos. Geogr. Obshch (notes from the State Geogr. Soc.), v. 71, No. 7, pp. 1078-1080, 1939.

(4) Underground ice; frost in soils

H. B. Atkinson and C. E. Bay, Some factors affecting frost-penetration: A summary, Trans. Amer. Geophys. Union, Part I, pp. 121-122, 1940.

H. B. Atkinson and C. E. Bay, Some factors affecting frost-penetration, Trans. Amer. Geophys. Union, Part III, pp. 935-949, 1940.

K. T. Belotelkin, Soil freezing and forest cover, Mimeo., U. S. Dept. Agric., N. E. For. Exp. Sta., Tech. Note No. 37, 1940.

ICE--Continued

(4) Underground ice; frost in soils--Concluded

H. U. Fuller, Frost penetration, J. Maine Water Utilities Assoc., pp. 41-48, 1940.

H. U. Fuller, Studies of frost penetration, J. N. E. W. W. Assoc., v. 54, No. 3, pp. 275-281, 1940 (Tabulations and diagrams indicating frost penetration of gravel and clay, experiment carried on by the Portland, Maine Water District).

E. R. Harrington, Desert refrigerator: Crystal ice cave in New Mexico, Refrig. Eng., v. 40, p. 11, July 1940.

Index to the literature on frost problems, 304 items listed by S. Maksimov in Met. i Hydro., No. 4, pp. 129-136, 1940.

Ya. B. Itter, Intensity of the layer of perpetual icing in the Verkhoyansk district, Problemy Arktiki, No. 6, pp. 85-86, 1939 (in Russian).

U. Nakaya and T. Magono, On the mechanism of frost heaving, I. The general survey in the field, J. Met. Soc. Japan, second ser., v. 18, No. 10, p. 35, 1940.

I. S. Novozhenov, Investigations on the depth of frost in soils, Trudy Uralskovo Industr. Inst., Ser. 2, pp. 57-70, 1939 (in Russian).

R. K. Schofield, Note on the freezing of soil, Quart. J., v. 66, No. 285, pp. 167-170, 1940.

(5) Polar

B. Aagaard, Who discovered Antarctica? Proc. Sixth Pac. Sci. Cong. Pac. Sci. Assoc., 1939, v. 2, pp. 675-707, 1940.

A. M. Acock, Vegetation of a calcareous inner fjord region in Spitsbergen, J. Ecology, v. 28, No. 1, pp. 81-106, 1940.

J. Q. Adams, Settlements of the Northeastern Canadian Arctic, Geophys. Rev., pp. 112-127, 1941.

H. W. Ahlmann, Norges ockupation i Antarktis, Ymer., Håft 1, pp. 84-86, 1939.

H. W. Ahlmann, Farden till Nordostgronland Sommaren, 1939, Ymer. Håft 4, pp. 257-282, 1939.

H. W. Ahlmann and S. Thorarinsson, Vatnajökull: Scientific results of the Swedish-Icelandic investigations 1936-1937, Geograf. Ann., Arg. 19, Heft 3-4, pp. 146-231, 1937; Arg. 20, Heft 3-4, pp. 171-233, 1938; Arg. 21, Heft 1, pp. 39-66, 1939; Arg. 22, Heft 3-4, pp. 188-205, 1940.

H. W. Ahlmann and S. Thorarinsson, Vatnajökull: Scientific results of the Swedish-Icelandic investigations, 1936-37-38, Chap. 7, H. W. Ahlmann, The regime of Hoffellsjökull; Chap. 8, S. Thorarinsson, Hoffellsjökull, its movements and drainage; Chap. 9, S. Thorarinsson, The ice dammed lakes of Iceland with particular reference to their values as indicators of glacier oscillations, Geog. Ann., Heft 3-4, pp. 171-242, 1939.

W. Albee, Kanguk, a boy of Bering Strait, Boston, Little, Brown and Company, 116 pp., 1939.

N. P. Anikeev and A. I. Gussev, Geologicheski ocherk yugo-zapadnoi chasti Taimirskogo poluostrova (The outline on geology of the south-western territory of the Taimyr Peninsula), Trudi articheskogo nauchno-issledovatelskogo instituta glavnogo upravleniya severnogo morskogo puti pri SNK, USSR (Trans. Arctic Inst. Chief Admin. Northern Sea Route), v. 134, Leningrad, p. 120, 1939.

Antarctic Pilot, Supplement No. 8--corrected to 16th December 1939, London, H. M. Stationery Office, 65 pp., 1940.

Arctic Pilot, v. 1, Supplement No. 5--corrected to 30 December, 1939, 1940, 108 pp., v. 2, Supplement No. 4--corrected to 29 September 1939, London, H. M. Stationery Office, 26 pp., 1940.

Baare-Schmidt, Hans-Georg, Alaska--Land der Zukunft, Zs. Geopolitik Jahrg. 15, Heft 9, pp. 723-729, 1938.

F. Bader, Communication sur les travaux dans les bouches du Iennissei, Soc. Geog. l'URSS, Izv., v. 71, No. 4, pp. 580-601, 1939 (in Russian).

K. Badigin, Meteorological observations on the icebreaker Georgii Sedov, Pogoda, No. 8, pp. 15-18, September 1940 (in Russian).

K. Badigin, Meteorological observations on the icebreaker Georgii Sedov, Pogoda (Weather), No. 8, pp. 15-18, September 1940 (in Russian).

T. W. Bagshawe, Two men in the antarctic: An expedition to Graham Land 1920-1922, Macmillan, 292 pp., 1939.

T. F. W. Barth, Notes on igneous and palingenic rocks from the Antarctic Archipelago: A contribution to the petrology of circum-Pacific rock types, Proc. Sixth Pac. Sci. Cong., Pac. Sci. Assoc., 1939, v. 2, pp. 747-754, 1940.

B. Bartlett, Arctic outposts of our defense, N. Y. Times Mag., pp. 6-7, April 20, 1941.

R. A. Bartlett, Greenland from 1898 to now, Nat. Geog. Mag., v. 78, pp. 111-140, July 1940.

ICE--Continued

(5) Polar--Continued

E. P. Bayliss and J. S. Cumpston, Handbook and index to accompany a map of Antarctica, produced by the Department of the Interior, Canberra, Australia, 90 pp., 1939.

W. Bege, Geomorphologische Forschungen im nördlichen Andreeland, Nord Spitzbergen (Doctoral thesis), Lengerich i. W., 112 pp., 1939.

K. Bell, Ice patrol (Account of the U. S. Coast Guard's Service in the North Atlantic), London, Routledge and Sons, 262 pp., 1940.

P. M. Bennett, The British Canadian Arctic Expedition, Geog. J., v. 95, No. 2, pp. 109-120, 1940.

R. Bentham, Structure and glaciers of southern Ellesmere Island, Geog. J., v. 97, No. 1, pp. 36-45, 1941.

C. Bertram, Arctic and Antarctic: The technique of polar travel, W. Heffer and Sons, Ltd., Cambridge, Eng., 125 pp., 1939.

A. I. Berzin, and others, Geologisheskie isseldovaniya Nordvik-Khatangskogo raiona i Taimyrskogo polyostrova (Geological investigations of the Nordvik-Khatanga region and of the Taimyr Peninsula), Central Admin. Northern Sea Route, Leningrad, 144 pp., 1938.

E. G. Bird, Jan Mayen, Geog. J., v. 95, No. 2, p. 156, 1940.

G. H. Blanchett, Conquering the northern air, Beaver, Outfit 269, No. 4, pp. 11-14, 1939 (Air transport in northern Canada).

F. W. Borgman, Klima und Politik im Eismeer: Die Temperaturverschiebungen in der eurasischen Arktis, Zs. Geopolitik, Jahrg. 15, Heft 6, pp. 439-450, 1938.

M. K. Bovey, Huskies over ice, Beaver, Outfit 269, No. 2, pp. 16-21, 1938 (Journey in August 1923 from Norway House on Lake Winnipeg to York Factory on Hudson Bay).

D. L. Brainard, Six came back: The Arctic adventure of David L. Brainard, Bobbs, 305 pp., 1940.

A. Breese, What is going on in the Russian Arctic? Bull. Amer. Met. Soc., v. 21, No. 7, p. 291, 1940.

E. T. Browne and P. L. Kramp, Hydromedusae from the Falkland Islands, Discovery Reports, v. 18, pp. 265-322, Cambridge, 1939.

G. S. Bryan, The Wilkes Exploring Expedition, Proc. U. S. Naval Inst., v. 65, No. 440, pp. 1452-1464, 1939.

M. J. Buerger, Spectacular Frobisher Bay, Can. Geog. J., v. 17, No. 1, pp. 3-18, 1938.

K. V. Bülow, Die Ross-Barriere und die Filchner-Barriere, Kosmos, Heft 6, pp. 208-209, 1938.

R. E. Byrd, Allein auf einsamer Wacht im Südeis, N. Y., 1938; Leipzig, Brockhaus, 1939.

Byrd Antarctic Expedition, 1939-41: The Antarctic "snow cruiser", Engineer, v. 169, No. 4399, pp. 413-415, 1940.

Byrd Antarctic Expedition, 1939-41: Hearings before the Subcommittee of the Committee on Appropriations, a Joint Resolution making an appropriation to the Dept. Int., Div. Terr. Isl. Poss. for expenses of Expedition to Antarctic regions, House of Representatives, 76th Cong., 1st session on H. J. Res., 310, Washington, 13 pp., 1939.

S. A. C. Campbell, and others, Soundings, B. A. N. Z. Antarctic Research Expedition, 1929-31, Reports, Ser. A, v. 3, Part 1, Adelaide, 1939.

W. S. Carlson, Greenland lies north, New York, Macmillan, 306 pp., 1940.

H. Carmichael and E. G. Dymond, Upper air investigations in north-west Greenland, Proc. R. Soc. London, Ser. A, v. 171, No. 946, pp. 345-359, 1939.

H. Carmichael and E. G. Dymond, High altitude cosmic radiation measurements near the North Geomagnetic Pole, Proc. R. Soc. London, Ser. A, v. 171, No. 946, pp. 321-344, 1939.

Hugh Carrington, The life of Captain Cook, London, Sidgwick and Jackson, 324 pp.

Centenary celebration: The Wilkes Exploring Expedition of the United States Navy, 1838-1842 and symposium on American polar exploration, Proc. Amer. Philos. Soc., v. 82, pp. 519-950, 1940.

Centenary Celebrations of the Wilkes Exploring Expedition and symposium on American polar exploration, Geog. Rev., v. 30, No. 2, pp. 323-325, 1940.

E. I. Chaplygin, Soil temperatures in the Arctic, Problems of the Arctic, v. 9, pp. 67-74, 1939 (in Russian).

L. Cohen, De Noordpool veroverd, Tijdschrift voor het onderwijs in de aardrijkskunde, Jaarg. 16, Alf. 5, pp. 73-87, 1938.

W. W. Coleman, Whale meat for huskies, Beaver, Outfit 269, No. 4, pp. 42-44, 1939.

V. Conrad, Scientific results of the Alfred Wegener German Greenland Expedition, 1929 and 1930-31, an abstract from v. 4, Part 1, Meteorology, by J. Georgi, R. Holzapfel, and W. Kopp, Bull. Amer. Met. Soc., v. 21, No. 9, p. 378, 1940.

V. Conrad, British Polar Expedition, Fort Rae, NW-Canada 1932-33: V. 1, Discussion of results, Meteorology, Terrestrial magnetism and Aurora, Atmospheric electricity; v. 2, Tables. Bull. Amer. Met. Soc., v. 22, No. 2, pp. 89-91, 1941.

ICE--Continued

(5) Polar--Continued

E. B. Copeland, Fern evolution in Antarctica, Philippine J. Sci., v. 70, No. 2, pp. 157-158, 1939.

Arnold Court and H. G. Dorsey, Jr., Antarctic weather observations, Bull. Amer. Met. Soc., v. 21, No. 9, pp. 386-387, 1940.

Leland Curtin, South of the Southern Cross, Sierra Club Bull., v. 26, No. 1, pp. 95-101, February 1941.

J. Daugaard-Jensen, The old and the new Greenland (account of progress in Administration), Congrés International des Sciences Anthropologiques et Ethnologiques, C.-R. 2^{e} Session, Copenhague, 1938, Copenhagen 1939, pp. 95-106.

John K. Davis, Soundings, Sci. Reps. Australasian Antarc. Exped. 1911-14, Ser. A, v. 2, Part 3, pp. 91-102, 1940.

Paul Davoud, Wings for Hudson Bay Company, Beaver, Outfit 269, No. 4, p. 15, 1939.

F. L. M. Dawson, The Cambridge (Myvatn) Iceland Expedition, 1939, Geog. J., v. 95, No. 6, pp. 439-451, 1940.

Frederica De Laguna, Man's sub-Arctic ally (the reindeer), Frontiers, v. 3, No. 2, pp. 48-54, 1938.

G. de Poncins, King William Land, Atlantic Mon., v. 167, pp. 81-90, January 1941.

G. de Poncins, Kabloona: Story of a journey into the North, Atlantic Mon., v. 166, pp. 545-553, 1940; Reynal and Hitchcock, New York, 339 pp., 1941.

G. de Poncins and L. Galantiere, Kabloona (abridged), Read. Dig., v. 38, pp. 141-168, June 1941.

G. E. R. Deacon, Carbon dioxide in Arctic and Antarctic Seas, Nature, v. 145, No. 3668, pp. 250-252, 1940.

Wilhelm Dege, Die heutige Besiedlung und Wirtschaft Spitsbergens, Petermanns Geog. Mitt., Jahrg. 85, Heft 5, pp. 166-171, 1939.

Wilhelm Dege, Vorläufiger Bericht über meine Spitsbergenfahrt 1938, Petermanns Geog. Mitt., Jahrg. 85, Heft 5, pp. 162-166, 1939.

Max Demorest, Glaciological research contemplated for an expedition to North Greenland, Trans. Amer. Geophys. Union, Part I, pp. 492-497, 1938.

Die Deutsche Antarktische Expedition, 1938-39, Polarforschung, Jahrg. 9, pp. 1-6, November 1, 1939.

Aubrey Diller, The mysterious arctic traveller of 1360, Nicholas of Lynn, Isis, v. 30, No. 81, pp. 277-278, 1939.

A. B. Dobrowolski, Sur le rôle historique du voyage de la Belgica, Bull. Soc. R. Belge de Géog., 63^{e} année, Fasc. 1, pp. 1-10, 1939.

A. T. Doodson, Tidal observations, Sci. Reps. Australasian Antarc. Exped. 1911-14, Ser. A, v. 2, Part 2, Sydney, pp. 65-85, 1929.

A. B. Edwards, Tertiary lavas from the Kerguelen Archipelago, B. A. N. Z. Antarc. Res. Exped., 1929-31, Reps., Ser. A, v. 2, Part 5, pp. 69-100, 1938.

V. Einarsson, Iceland, land of frost and fire, Can. Geog. J., v. 21, pp. 172-191, 1940.

R. A. J. English, Preliminary account of the U. S. Antarc. Exped., 1939-1941, Geog. Rev., pp. 466-478, 1941.

Expedition to the Antarctic; under Admiral Byrd: It finds 900 miles of new coastline, Life, v. 9, pp. 27-33, July 8, 1940.

Exploring a frozen continent, Pop. Mech., v. 75, pp. 50-53, January 1941.

H. V. Ficker, Meteorologische Ergebnisse der Deutschen Grönlandexpedition Alfred Wegener, Met. Zs., Band 57, Heft 5, pp. 185-191, 1940.

Richard Finnie, Lure of the North, David McKay Company, Philadelphia, 227 pp., 1940.

The first steamship in Arctic exploration, Geog. J., v. 95, No. 2, pp. 131-132, 1940.

Launcelot Fleming, Colin Bertam, and Brian Roberts, Three Antarctic years: The British Graham Land Expedition of 1934-1937, Can. Geog. J., v. 22, No. 1, pp. 3-39, 1941.

W. L. S. Fleming, Relic glacial forms on the western seaboard of Graham Land, Geog. J., v. 96, No. 2, pp. 93-100, 1940.

John Ripley Forbes, Where winter and summer meet--a new nesting ground of the Greenland Wheatear is discovered on an eventful voyage to Baffin Island with the 1937 MacMillan Expedition, Nat. Hist., v. 42, No. 1, pp. 58-65, 1938.

Harry A. Franck, The lure of Alaska, New York, F. A. Stokes and Company, 306 pp., 1939.

Herbert Friedmann, Further records from St. Lawrence Island, Alaska, Condor, v. 40, p. 88, 1938.

Angus Gavin, A series of photographs of breathing-hole sealing by Vicompte Gontran de Poncin, Beaver, Outfit 270, No. 4, pp. 26-31, 1940.

Pierre George, Contribution de l'expédition Papanine à la géographie physique, Ann. Geog., 47^{e} année, No. 270, pp. 645-647, 1938.

ICE--Continued

(5) Polar--Continued

J. Georgi, Im Eis vergraben, Munich, Verlag des Blodigschen Alpenkalenders Paul Müller, 1940, fifth enlarged Ed., reviewed by U. Charisius in Ann. Hydrogra., Heft 11, p. 400, 1940.

Georgi, Dem Polarforscher Kapitän Ejnar Mikkelsen zum 60. Befurtstag, Ann. Hydrogra., Heft 12, pp. 431-433, 1940.

W. Gibson, Amundsen in King William Land, Beaver, Outfit 271, No. 1, pp. 32-38, 1940.

W. Gibson and J. G. Cormack, Building a snow house, Beaver, Outfit 270, No. 4, pp. 40-41, 1940.

J. O. Glastonbury, Acid effusive and hypabyssal rocks (from the moraines), Sci. Reports, Australasian Antarctic Expedition, 1911-14, Ser. A, v. 4, Part 4, pp. 117-134, Sydney, 1940.

L. M. Gould, The glacial geology of the Pacific Antarctic, Proc. Sixth Pac. Sci. Cong., Pac. Sci. Assoc., 1939, v. 2, pp. 723-740, 1940.

L. M. Gould, Antarctic regions, Proc. Sixth Pac. Sci. Cong., Pac. Sci. Assoc., 1939, v. 2, pp. 671-674, 1940.

G. Grandidier, La Terre Adélie, Renseignements coloniaux, Nos. 8 and 9, pp. 190-194, 1938.

Greenland, Des noms français sur la carte de Greenland, l'Illustration, 97^{e} année, No. 5015, pp. 471-473, 1939.

G. Grimminger, Meteorological results of the Byrd Antarctic Expeditions 1928-30, 1933-35: Tables, Mon. Weath. Rev., Supp. No. 41, 377 pp., 1939.

I. G. Guterman, The thermal structure up to 20 kilometres over Franz Joseph Land, Bull. Amer. Met. Soc., v. 19, No. 10, pp. 433-436, 1938.

David Haig-Thomas, Expedition to Ellesmere Island, 1937-38, Geog. J., v. 95, No. 4, pp. 265-277, 1940.

D. C. Haskell, The United States Exploring Expedition, 1838-1842, and its publications, 1844-1874: A bibliography, Bull. N. Y. Pub. Lib., v. 45, No. 1, pp. 69-89, 1941.

O. A. Hög, On crusts of gypsum on the soil at Klaas Billen Bay, Spitsbergen, Norske Videnskabers Selskab Forhandlinger, v. 12, No. 31, pp. 111-114.

A. Heim, Einige Beobachtungen über Eis und Schnee auf Novaya Zemlya, Zs. Gletscherkunde, v. 26, pp. 137-140, 1938-39.

Y. Henderson and J. McC. Turner, Carbon monoxide as a hazard of polar exploration, Nature, v. 145, No. 3664, pp. 92-95, 1940.

E. Herrmann, Die Deutsche Antarktische Expedition 1938-39, Zs. Erdkunde, No. 13/16, 1940.

E. Herrmann, Wege zum Nordpol. Forscher und Abenteurer im ewigen Eis, Braunschweig, Menzel und Sohn, 288 pp., 1940.

A. R. Hinks, The log of the Hero, Geog. J., v. 96, No. 6, pp. 419-430, 1940; discussion of Lawrence Martin's "Antarctica discovered by a Connecticut Yankee," Geog. Rev., October 1940.

A. R. Hinks, Antarctica discovered: A reply, Geog. Rev., pp. 491-497, 1941.

A. R. Hinks, Maps of the world on an oblique Mercator projection, Geog. J., v. 95, No. 5, pp. 381-383, 1940.

C. Hoare, Herschel Island to Aklavik, 1923, Beaver, Outfit 269, No. 3, pp. 42-45, 1938.

W. H. Hobbs, Antarctic names, Proc. Sixth Pac. Sci. Cong., Pac. Sci. Assoc., 1939, v. 2, pp. 709-714, 1940.

W. H. Hobbs, The defense of Greenland, Ann. Assoc. Amer. Geog., v. 31, No. 2, pp. 95-104, 1941.

W. H. Hobbs, Early maps of Antarctic land, true and false, Papers, Mich. Acad. Sci., Arts, Letters, v. 26, pp. 401-405, 1940.

W. H. Hobbs, Explorers of the Antarctic, N. Y., House of Field, Inc., 334 pp., 1941.

W. H. Hobbs, Reports of the Greenland Expeditions of the University of Michigan, Part 2, Meteorology, Physiography, and Botany, Univ. Mich. Press, 287 pp., 1941.

W. H. Hobbs, The pack ice of the Weddell Sea, Ann. Assoc. Amer. Geog., v. 29, No. 2, pp. 159-170, 1939.

A. Hoel, Die Verwendung von Luftfahrzeugen bei der Erforschung der Polargebiete, Zs. Erdkunde zu Berlin, Jahrg. 6, Heft 5-6, pp. 161-175, 1938.

D. Holdridge, Arctic lights, London, Robert Hale, Ltd., 240 pp., 1940.

R. Holzapfel, W. Kopp, and Kurt Wegener, Wissenschaftl. Ergebn. der Deutschen Grönland-Expedition, A. Wegener, 1929 und 1930-31, Bd. 4, Meteorologie 2, Halbband: Die Ergebnisse, Leipzig, F. A. Brockhaus, 380 pp., 1939.

S. G. Horner, Posts of the far north will have two-way short wave communication, Beaver, Outfit 269, No. 1, pp. 10-13, 1938.

D. Irwin and F. M. Reck, One man against the North, Crowell, 244 pp., 1940.

F. Isachsen, The new Norwegian Dependency in the Antarctic, Le Nord: Internat. Rev. Northern Countries, 1939, No. 1, Copenhagen, Helsingfors, Oslo, Stockholm, pp. 67-78, 1939.

ICE--Continued

(5) Polar--Continued

M. Jåderin-Hagfors, Min Far Upplever Polarnatten: Edward Jåderins över-wintering på Spetsbergen för fyrtie år sedan, Stockholm, Bokförlaget Natur och Kultur, 176 pp., 1939.

F. Jankuhn, Politisch-geographische Betrachtungen über Lappland, Zs. der Ges. Erdkunde zu Berlin, Jahrg. 6, Heft 8, pp. 322-326, 1938.

A. S. Jensen, Concerning a change of climate during recent decades in the Arctic and sub-Arctic regions, from Greenland in the west to Eurasia in the east, and contemporary biological and geophysical changes, K. Danske Vidensk. Selskab. Biol. Medd., v. 14, No. 8, 75 pp. 1939.

O. v. Johansson, Der jährliche Gang der Temperatur in polaren Gegenden, Geog. Ann., Arg. 21, Heft 2, pp. 89-118, 1939.

W. Jost, Gletscherschwankungen auf der Insel Disco in Westgrönland, Zs. Gletscherkunde, Bd. 27, Heft 1-2, pp. 20-26, 1940.

H. F. Kellens, We tried to solve an Arctic mystery, Alaska Sportsman, v. 6, No. 6, pp. 10-11 and 32-33, 1940.

E. M. Kindle, Recent glacial studies of the Nugssuak Region, West Greenland, J. Geol., v. 46, No. 6, pp. 882-888, 1938.

Lauge Koch, Survey of North Greenland, København, 1940, 364 pp., 21 maps, Meddelelser om Grønland, Bd. 130, Nr. 1 [Contents: (1) The Smith Sound Route and the first journeys along the north coast of Greenland; (II) Robert Edwin Peary; (III) Danish expeditions to East and North Greenland, first period 1906-23; (IV) Danish expeditions to East and North Greenland, second period 1933-38].

E. Kohlschutter, Die Lage der Station "Eismitte", Petermanns geogr. Mitt., Jahrg. 86, Heft 12, pp. 406-409, 1940.

N.-H. Kolderup and A. Kvale, Jordskjelvet på Jan Mayen 26 Oktober 1936 og Seiomikkon i Norskehavet og Nordsjoen, Bergens Museums Arbok, Naturvidenskapelig rekke, Heft 1, Nr. 3, pp. 24-25, 1938.

A. Kortland, Lapland, Een sociaal-geografische studie naar aanleiding van reisen in 1934 en 1935, Ts. Kon. Nederl. Aardr. Gen., v. 56, No. 4, Amsterdam, pp. 543-558, 1939.

D. la Cour, Rapport du President de la Commission Internationale de l'Année polaire 1932-1933, Secréteriat l'Organization Mét. Internat., No. 40, pp. 141-145, 1938.

S. A. Korff and E. T. Clarke, Report of cosmic ray observations made on the U. S. Antarctic Expedition in cooperation with the Bartol Research Foundation, J. Franklin Inst., v. 230, pp. 567-581, 1940.

A. Laktionov, The task of the glaciologic and hydrologic investigations in the Arctic, Problemy Arktiki, No. 6, pp. 5-10, 1939 (in Russian).

Limites des territoires français de la région antarctique dite "Terre Adélie", Chronique Mines Coloniales, 7^e année, No. 74, pp. 169-170, 1938.

A. A. Lindsey, Recent advances in Antarctic bio-geography, Quart. Rev. Biol., v. 15, No. 4, pp. 456-465, 1940.

B. Lynge, Lichens from the west and north coasts of Spitsbergen and North East Land, collected by numerous expeditions, Skrifter utgitt av Det Norske Videnskaps-Akad. i Oslo, I. Math-Naturv. Klasse, No. 6, pp. 1-136, 1938.

C. J. MacGregor, The MacGregor Arctic Expedition to Etah, Greenland, July 1, 1937, to October 4, 1938, Mon. Weath. Rev., Washington, pp. 366-382, October 1938.

N. A. Mackintosh and H. F. P. Herdman, Distribution of the pack-ice in the Southern Ocean, Discovery Reports, v. 19, pp. 285-296, Pl. 69-95, 1940.

D. L. McKeand, The annual eastern Arctic patrol, Can. Geog. J., v. 17, No. 1, pp. 37-39, 1938.

T. E. M. McKitterick, The validity of territorial and other claims in polar regions, J. Comp. Legislation and Internat. Law, Third Ser., v. 21, Part 1, pp. 89-97, 1939.

O. M. McMillan, New Alaska, Ann Arbor, Mich., Edward Bros., 216 pp., 1939.

V. Madsen, À propos de la chaîne Calédonienne du Groenlandseptentrional, C.-R. Séancés Acad. Sci., v. 206, No. 19, pp. 1389-1391, 1938.

Map of perpetual ice in the territory of the USSR, Bol'shoi Sovetski Atlas Mira (Great Sovietic World Atlas), pp. 90-91.

R. S. Marriot, Canada's eastern Arctic patrol, Can. Geog. J., v. 20, No. 3, pp. 156-161, 1940.

L. Martin, An American discovered Antarctica, C.-R. Congrès Internat. Géog., v. 2, Travaux de la Section 4, pp. 215-218, 1938.

K. Mason, Notes on the northern sea route, Geog. J., v. 96, No. 1, pp. 27-41, 1940.

D. Mawson, A. Howard, and H. U. Sverdrup, Hydrology, Introduction and appendices by D. Mawson: Section 1, The programme of work and record of observations, by A. Howard; Section 2, Discussion by H. U. Sverdrup, B. A. N. Z. Antarctic Res. Expedition 1929-1931, Reports, Ser. B, v. 3, Part 2, pp. 25-126, 1940.

ICE--Continued

(5) Polar--Continued

D. Mawson, Ed., Meteorology: Part 1, Records of the Queen Mary Land Station, recorded by M. H. Moyes; Part 2, Meteorological log of the S. Y. Aurora, recorded by P. Gray; Part 3, Sledge journey weather records, by various observers, Sci. Reports Australasian Antarctic Exped. 1911-1914, Ser. B, v. 5, p. 281, 1940.

D. Mawson, Antarctic research, Australian J. Sci., v. 1, No. 1, pp. 9-11, 1938.

D. Mawson, Hydrological observations made on board S. Y. Aurora, reduced, tabulated and edited, Sci. Reports Australasian Antarctic Exped. 1911-1914, Ser. A, v. 2, Part 4, pp. 107-125, 1940.

L. Mecking, Die Periodizität der Eisbedeckung in der Davis-Strasse, Ann. der Hydrogr., Jahrg. 67, Heft 1, pp. 23-26, 1938.

W. Meinardus, Klima der Antarktis, Forsch. Fortschr., 1, 1940.

W. Meinardus, Klimakunde der Antarktis, Köppen-Geiger, Handbuch der Klimatologie, Bd. 4, Teil 8, Berlin, Gebr. Borntraeger, 1938, 133 pp.; reviewed in Ann. Hydrogr., pp. 138-140, April 1940.

Meteorologische Beobachtungen deutscher Schiffe im Europäischen Nordmeer und in der Barentssee während des Zweiten Internationalen Polarjahres 1932-33, Archiv. Deutschen Seewarte und des Marine-observatoriums, Bd. 59, No. 3, pp. 1-39.

Meteorological results of the Byrd Antarctic Expeditions 1928-30, 1933-35: Summaries of data, Mon. Weath. Rev., Supp. No. 42, U. S. Dept. Agric., Weather Bureau.

H. R. Mill, Antarctic exploration, J. Manchester Geog. Soc., v. 49, 1938-1939, pp. 23-25, 1938-39.

S. Mogilevska, The camp on the ice field, London, Routledge and Sons, 232 pp., 1940.

J. M. Moneta, Por nuestros mares australes, Desde Georgia del Sud a las Islas Orcadas, Rev. geogr. americana, v. 14, No. 87, pp. 391-404, 1940.

R. Moss, Atmospheric optical phenomena in North East Land, Quart. J., v. 64, No. 276, pp. 451-458, 1938.

E. Neaverson, General characters of sea-floor deposits from the Bellingshausen Sea and western coast of South America, Proc. Sixth Pac. Sci. Cong., Pac. Sci. Assoc., 1939, v. 2, pp. 779-781, 1940.

D. A. Nichols, Greenland, Our Northeastern neighbor, Can. Geog. J., v. 22, No. 1, pp. 41-55, 1941.

D. A. Nichols, Arctic tides and currents, Beaver, Outfit 270, No. 4, pp. 19-22, 1940.

S. R. Nockolds, Petrology of rocks from Queen Mary Land, Australasian Antarctic Exped., Sci. Reports, 1911-14, Ser. A, v. 4, Part 2, pp. 19-86, 1940.

J. J. O'Neill, Byrd-Ellsworth findings vital on topography, Polar Times, p. 23, March 1940.

Operations in the Soviet Arctic in 1940, For. Comm. W., v. 1, pp. 116-117, October 19, 1940.

H. Ostermann, Nordmaend paå Grønland, 1721-1814, Oslo, Gyldendal Norsk forlag, 2 v., maps, 52 pp., 1940.

Russell Owen, The Antarctic Ocean, maps (oceans of the world) by Stephen J. Voorhies, New York, Whittlesey House, McGraw-Hill Book Company, Inc., 254 pp., 1941.

D. Panov, La nature de la partie centrale de l'Arctique et les travaux scientifiques de la station sovietique en derive "Pole Nord", Izv. Soc. Russe Geog., v. 70, No. 3, pp. 335-349, 1938.

I. D. Papanin, Zhisn na l'dine (Life on ice), Moscow, published by the North Sea Route Commission, 414 pp., 1940.

T. T. Paterson, The effects of frost action and solifluxion around Baffin Bay and in the Cambridge district, Quart. J. Geol. Soc. London, v. 96, No. 381, pp. 99-130, 1940.

A. Pedersen, Et naturens-reservat, Copenhagen, Gyldendal, 66 pp., 1940.

Petsamo-Kola, The northern Finno-Russian frontier, Geog. Rev., v. 30, No. 1, pp. 149-152, 1940.

C. H. Pollog, Die Motorisierung der Südpolarforschung--Ergebnisse und Erwartungen, Mitt. Geogr. Ges. in Wien, Bd. 82, Nr. 1-2, pp. 24-37, Nr. 3-4, pp. 82-93, 1939.

H. Poser, Deutsche Forschung in den Polarländern seit dem Weltkriege, Geog. Zs., No. 7/8, 1940.

C. Poulsen, A propos de l'Ozarkien au Groenland, C.-R. Séances Acad. Sci., v. 206, No. 19, pp. 1391-1393, 1938.

N. Pye, Some geographical observations during an expedition to Billefjorden, Spitsbergen, J. Manchester Geog. Soc., v. 49, pp. 26-47, 1938-39.

C. Rabot, En dérive pendant neuf mois sur un glaçon polaire, l'Illustration, 96^{e} année, No. 4970, pp. 183-189, 1938.

B. Raptschinsky, De economische beteekens is van het hooge noorden in Rusland, Tijdschrift v. economische Geogr., Jaarg. 29, No. 9, pp. 193-201, 1938.

ICE--Continued

(5) *Polar*--Continued

Rasskazy Sedovtsev (Tales of the members of the ship *Georgii Sedov*, Book 2, published by the North Sea Route Commission, Moscow, 478 pp., 1940.

G. W. Rayner, MacRobertson Land and Kemp Land 1936, with a report on rock specimens, by C. E. Tilley, Discovery Reports, v. 19, pp. 165-184, 1940.

Recent polar publications, Polar Times, No. 10, Supp. 41, Mimeo., March 1940.

Reprinted newspaper accounts of polar explorations, Polar Times, Amer. Polar Soc.

Return (Byrd Expedition, 1939-41), Time, v. 37, p. 25, April 21, 1941.

W. Richling-Kondracka, Nowa Ziemia w 'swietle ostatnich badań, Przeglad Geograficzy, v. 18, pp. 133-154, 1938.

H. Rieche, Vorläufiger Bericht über die Ergebnisse der Deutschen Spitzbergen-Expedition 1937, Polarforschung, Jahrg. 8, Heft 1, pp. 1-4, 1938.

Felix Riesenberg, Cape Horn, Dodd, Mead, and Company, New York, 452 pp., 1939.

B. Roberts, Notes on the Barrow collection of Arctic equipment, Geog. J., v. 95, No. 5, pp. 368-380, 1940.

J. Rouch, Le record français de latitude, Geographie, v. 81, No. 1, pp. 1-12, 1939.

J. Rouch, Cook et Peary, Revue général des Sci. pures et appliquées, v. 49, No. 7, pp. 169-172, 1938.

H. Rüdiger, Deutsche Forschungsarbeit in den Polargebieten, Zs. Erdkunde, No. 13/16, 1940.

H. Rüdiger, England unterschlägt deutsche Antarktis-Forschung, Deutschtum in Ausland, No. 5/6, 1940.

H. Rudolphi, Sowjetrussland in Nordasien und der Arktis, Geog. Zs., Jahrg. 44, Heft 10, pp. 371-386, 1938.

R. S. Russell and P. S. Wellington, Physiological and ecological studies on an Arctic vegetation: (I) The vegetation of Jan Mayen Island, Ecology, v. 28, No. 1, pp. 153-179, 1940.

Ruthe, Die Erschliessung der russischen Arktis, Polarforschung, No. 1, 1940.

J. Rymill, Southern lights, the official account of the British Graham Land Expedition of 1934-37, Harper Brothers, 271 pp., 1939.

R. Sand, Knud Rasmussen-Museet i Hundested, Aarsskrift det Grønlandske Selskabs, pp. 105-113, 1939.

A. Saunders, Adventures in the Antarctic, Geog. Mag., v. 12, No. 2, pp. 118-131, 1940.

A. Scott, Arctic Bay to Igloolik, Beaver, Outfit 269, No. 3, pp. 14-18, 1938.

O. J. Schmidt, L'exploration de l'Arctique en Union Soviétique, C.-R. Cong. Internat. Géogr., Varsovie, 1934, v. 4, pp. 355-370, 1938.

K. Schmitt, Gipfelfahrten in der Arktis, Zs. Deutschen Alpenvereinds, Bd. 69, pp. 202-208, 1938.

G. Seaver, Scott of the Antarctic: A study in character, London, John Murray, 196 pp., 1940.

L. Segal, Conquest of the Arctic, Oxford, Toronto, 284 pp., 1939.

G. Seidenfaden, Modern Arctic exploration, Hale, Cushman, and Flint, N. Y., 189 pp., 1940.

A. Seifert, Staatenwiftschaftliche Länderschau (Antarktis), Zs, Geopolitik, Jahrg. 15, No. 1, pp. 71-81, 1938.

O. A. Sibley, South polar Diesel performance; U.S.S. *Bear* in the Antarctic, Marine Eng., v. 45, p. 6305, 1940.

George Gaylord Simpson, Antarctic as a faunal migration route, Proc. Sixth Pac. Sci. Cong., Pac. Sci. Assoc., 1939, v. 2, pp. 755-768, 1940.

Nils Nilsson Skum, Same Sita-Lappbyn, Stockholm, Bökforlags Aktiebolaget Thule, 157 pp., 1938.

R. Spitaler, Der Einfluss kalter und warmer Jahreszeiten in Sibirien auf die Niederschlage in Europa, Met. Zs., Bd. 57, Heft 8, pp. 302-305, 1940.

J. M. Stagg, Magnetic disturbance at Cape Denison: Australasian Antarctic Expedition, 1911-14, under the leadership of Sir Douglas Mawson, Sci. Reports, Ser. B, Terrestrial magnetism and related observations, v. 2, Part III, pp. 337-450, 1940.

V. Stefansson, Mystery of arctic weather, Sci. Digest, v. 9, pp. 23-28, June 1941.

V. Stefansson, Ultima Thule; further mysteries of the Arctic (bibliography, pp. 363-365), Macmillan, 383 pp., 1940.

Vilhjalmur Stefansson, The disappearance of the Greenland Colony, Nat. Hist., v. 43, No. 1, pp. 7-12, 1939.

J. Stěhule, Nový spor o prvni dosaženi severního pólu, Sborník Československé Spolěcnosti zeměpione, Svasek 44, Sešit 1 a 2, pp. 19-24, 1938.

K. Stephenson, Zool. Ergebn. der Reisen von Dr. Kohl-Larsen nach den Subantarktischen Inseln bei Neu-Seeland und nach Süd-Georgien, Senckenbergiana, Bd. XX, Nr. 3 und 4, Frankfurt, pp. 236-264, 1938.

Duncan Stewart, Jr., Petrography of rocks from the Pacific Antarctic, Proc. Sixth Pac. Sci. Cong., Pac. Sci. Assoc., 1939, v. 2, pp. 741-746, 1940.

ICE--Concluded

(5) *Polar*--Concluded

Duncan Stewart, Jr., Notes on some Marie Byrd Land rocks, reprinted from Amer. Mineral., v. 26, pp. 42-49, 1941.

J. C. Sugden and P. G. Mott, Oxford University Greenland Expedition, 1938, Geog. J., pp. 43-51, January 1940.

H. S. Summers and A. B. Edwards, Granites of King George Land and Adélie Land, Sci. Reports, Australasian Antarctic Exped., 1911-14, Ser. A, v. 4, Part 3, pp. 89-113, 1940.

W. S. Swerchkov, Amderminskoe mestorozhdenio plavikovogo shpata, Trans. Arctic Inst. Chief Admin. Northern Sea Route, v. 134, Leningrad, 84 pp., 1939.

Curt Teichert, Corrosion by wind-blown snow in polar regions, Amer. J. Sci., v. 237, No. 2, pp. 146-148, 1939.

U. S. Army, Air Corps, Arctic manual, prepared under the direction of Chief of Air Corps, U. S. Army, Washington, 2 v., 1940.

To use carbon black in Arctic pictures: Powder dropped on snow will permit faster and more accurate overlapping aerial photographs, Rubber Age, v. 46, p. 183, 1939.

Trudy dreyfuyushohei stantsii *Severyni Polius* (Publications of the drifting station *North Pole*), pub. by North Sea Route Commission, Moscow, 1940, 334 pp. (Contents: Expedition to the Pole; The drifting station; The flight to the Pole; Radio station UPOL; Astronomical observations.)

V. I. Vize, Climatology of the Arctic seas, Problems of the Arctic, v. 3, pp. 45-54, 1940 (in Russian).

A. Wade, The geology of the Antarctic Continent and its relationship to the neighbouring land areas, Proc. R. Soc. Queensland, v. 52, No. 4, Brisbane, 12 pp., 1940.

Kurt Wegener, Scientific results of the German Greenland Expedition, Alfred Wegener, 1929 and 1930/31, v. 4, Part 2, Meteorology: The results, by R. Holzapfel, W. Kopp, K. Wegener; Supp. by J. Georgi, H. Jülg, E. Sorge (K. Wegener, Wissenchaftl. Ergebnisse d. Deutschen Grönlandexpedition Alfred Wegener, 1929 and 1930/31, Band IV. Meteorologie; 2. Halbband: Die Ergebnisse), F. A. Brockhaus, Leipzig, 380 pp., 1939.

F. W. White and M. Geddes, Antarctic zone of maximum auroral frequency, Terr. Mag., v. 44, No. 4, pp. 367-377, 1939.

H. G. Winkler, Vereisung des Glama-Plateaus in Nordwest-Island, Zs. Gletscherkunde, Bd. 26, pp. 199-214, 1939.

J. Wright, South-east Ellesmere Island, Geog. J., v. 95, No. 4, pp. 278-291, 1940.

G. Wüst, Das Problem des antarktischen Bodenstromes in Weltmeere, C.-R. Cong. Internat. de Géog., v. 2, Travaux de la section 11 b, pp. 45-48, 1938.

N. N. Zubov, The drift of the ice-breaker *Sedov*, Nature, No. 3675, pp. 533-539, 1940.

N. N. Zubov, Vetsentr arktiki (In the center of the Arctic), Moscow, 237 pp., 1940.

PHYSICS OF SNOW AND ICE

V. J. Altberg, Crystallisation properties of water, met. i Hydrol., Moscow, No. 3, pp. 59-67, 1939 (in Russian).

D. L. Arenberg, The formation of small hail and snow pellets, Bull. Amer. Met. Soc., v. 22, No. 3, pp. 113-116, 1941.

V. I. Arnold-Alabiev, Investigation of physical properties of solid hydro-meteors, Met. i Hydrol., No. 3, pp. 15-27, 1939 (in Russian).

N. T. Chernigovski, On the radiative properties of the snow cover and ice of the Arctic seas, Problemy Artiki, No. 6, pp. 31-38, 1939 (in Russian).

P. E. Church, Ice-crusts and snow-settling at Snoqualmie Pass, season of 1939-1940, Trans. Amer. Geophys. Union, Part III, p. 932, 1940.

N. Ernest Dorsey, Properties of ordinary water-substance in all its phases: Water vapor, water and all the ices, Reinhold Pub. Corp., 656 pp.

M. Golovkov, Investigation of ice formed on the airplanes, abstract from Bull. Acad. Sci. l'URSS, No. 1, p. 123, 1940; Bull. Amer. Met. Soc., v. 22, No. 2, p. 91.

A. G. Ingalis, Time it was settled: Which freezes quicker hot water or cold? Sci. Amer., v. 154, p. 132, March 1940.

H. M. Rose, Die Abhängigkeit der Leitfähigkeit des Schnees von seiner Kristallstruktur, Wetter, v. 57, No. 6, p. 190, 1940.

Nippon Setsuhyo Kyokai, Geppo (Jap. Assoc. of Snow and Ice, Monthly report), v. 2, No. 12, December 1940 (in Japanese).

PHYSICS OF SNOW AND ICE--Concluded

Nippon Setsuhyo Kyokai Zasshi, Setsu Hyo (Jap. Assoc. of Snow and Ice Mag.: Snow and Ice), v. 3, Nos. 1-6, January-June 1941 (in Japanese--Many problems on the physical nature of sea-ice in relation to the weather forecast, fisheries, navigation,and sea-engineering were remarked).

N. E. Odell, Ablation at high altitudes and under high solar incidence, Amer. J. Sci., v. 239, pp. 379-382, 1941.

T. Okabe, Experimental report on a few fundamental natures referring to the dynamics of deep snow, J. Met. Soc. Jap., pp. 144-148, April 1940.

N. S. Osborne, Heat of fusion of ice, J. Res. Nation. Bur. Stand., v. 23, pp. 643-646, 1939.

Preserves snow crystal, N. Y. Times, March 8, 1941 (method described in Science, March 6, 1941), Bull. Amer. Met. Soc., v. 22, No. 4, p. 186, 1941.

F. Prohaska und Chr. Thams, Neue Untersuchungen über die Strahlungseigenschaften der Schneedecke, Helvetica Physica Acta, v. 13, p. 21, 1940.

R. A. F. Weather reports include freezing level, Sci. News Letter, v. 39, p. 8, January 4, 1941.

V. J. Schaefer, Method for making snowflake replicas, Science, v. 93, pp. 240-241, 1941; abstract Sci. News Letter, v. 39, p. 172, March 15, 1941.

Mititaka Uda, Physical problems of the sea-ice in the northern waters adjacent to Japan ("Many problems on the physical nature of sea-ice in relation to the weather forecast, fisheries, navigation,and sea-engineering were remarked"); Nippon Setsuhyo Kyokai Zasshi, Setsu Hyo (Jap. Assoc. of Snow and Ice Mag.: Snow and ice), v. 3, No. 1, 1941 (in Japanese).

E. Wall and E. Huss, Einige merkwürdige und wenig bekannte Kristallisations-Erscheinungen des Eises, Z. a. Met., v. 57, pp. 84-90, 1940.

C. A. Wentworth, Ablation of snow under the vertical sun in Hawaii, Amer. J. Sci., v. 238, pp. 112-116, 1940.

MOUNTAINS, MOUNTAIN OBSERVATORIES, AND MOUNTAINEERING

Ansel Adams, Photography and Cedric Wright, Bull. Sierra Club, v. 26, No. 1, 1941.

A. E. Bent, Radio for mountaineers, Appalachia, v. 5, No. 12, pp. 497-502, 1939.

C. F. Brooks, The "worst" weather in the world, Geog. Rev., pp. 503-504, July 1941.

V. Conrad, How often does the air temperature pass the freezing point on Mount Washington? Mt. Wash. Obs., No. 8, pp. 13-14, January 1941.

D. F. Costello and R. Price, Weather and plant-development data as determinants of grazing periods on mountain range, Tech. Bull. U. S. Dept. Agric., No. 686, pp. 1-30, 1939; abstract Nat. Wool Grower, v. 30, p. 35, March 1940; pp. 17-18, May 1940.

W. R. Hainsworth, Mountain climber engineer, Pop. Sci., v. 138, pp. 95-97, January 1941.

Humberto Barrera V., Meteorologia de alta montaña, Rev. Chileña de Historia y Geogr., v. 89, No. 97, pp. 369-377, July-December, 1940.

A. Larrain, La alimentacion en la alta montaña y alta cordillera, Mem. tec. Ejercito de Chile, v. 8, No. 33, pp. 73-81, October-December, 1940.

C. F. Meade, Approach to the hills, Dutton, 265 pp., 1940.

Mount Washington observations, 1939, Mt. Wash. Obs., No. 6, pp. 6-7, 1939.

Research on the mountain, Mt. Wash. Obs., No. 8, pp. 1-2, January 1941.

Scaling new mountain tops: Peaks in western Canada, Can. Sci. Mon. Mag., p. 14, June 29, 1940.

K. Schwartz, Summer in California snowdrifts, Can. Sci. Mon. Mag., pp. 8-9, June 15, 1940.

F. S. Smythe, My Alpine album, Adam and Charles Black, London, 147 pp., 1940.

F. S. Smythe, Edward Whymper, Hodder and Stoughton, Ltd., London, 330 pp., 1940.

Steeplejacks of the mountain peaks, Pop. Mech., v. 74, pp. 546-549, 1940.

O. Steinböck, Arbeiten über die Limnologie der Hochgebirgsgewässer, Internat. Rev., Ges. Hydrobiol. u. Hydrogr., v. 37, pp. 467-509, 1938.

Kaare Munster Strëm, Moskenesöy: A study in high latitude cirque lakes, Skrifter utgitt av det Norske Videnskaps-Akad. i Oslo, I. Math.-Naturv. Klasse, No. 1, pp. 5-32, 1938.

J. Waller, The everlasting hills, Wm. Blackwood and Sons, Ltd., Edinburgh and London, 190 pp., 1939.

C. Wright, Mountain photography, Bull. Sierra Club, v. 26, No. 1, February 1941 (folio p. 14).

APPARATUS

B. Bagossy, Ein Gerät für die Fernmessung der Rauhreifdicke an Freileitungen, Az. Idöj., Budapest, v. 15, pp. 229-230, 1939 (in Magyar--German summary pp. 263-264; abstract in Italian, French, and English, p. 263).

P. W. Bean and F. A. Bendtsen, Snow-sampling equipment for granular and crusted snow in New England, Trans. Amer. Geophys. Union, Part III, pp. 916-920, 1940.

J. Chatillon and Sons, New spring-balances, Trans. Amer. Geophys. Union, Part III, pp. 908-909, 1940.

Chicago Eye Shield Co., Industrial head and eye protection, 24th catalog Ed., Pacific Metals Co., Ltd.

APPARATUS--Concluded

P. S. Cowgill, Improvement of snow-survey equipment, Trans. Amer. Geophys. Union, Part III, pp. 904-905, 1940.

P. S. Cowgill, Some handy kinks for field-men, Trans. Amer. Geophys. Union, Part I-B, pp. 108-109, 1940.

N. Nikolaiev, Soil evaporator-condensator, Met. i Hydrol., v. 7, p. 81, 1940 (in Russian).

B. Robinson, Equipment and technique for camping on snow, Bull. Sierra Club, v. 26, No. 1, pp. 38-47, 1937.

B. Robinson, Equipment and technique for camping on snow, Part II: The sectional tent, Bull. Sierra Club, v. 26, No. 1, pp. 90-95, 1941.

J. T. Ryan, Improvements to the Tucker motor-sled to surmount difficulties in traversing powder-snow, Trans. Amer. Geophys. Union, Part III, pp. 902-904, 1940.

J. C. Stevens, Tests of Mount Rose snow-scale No. 101, Trans. Amer. Geophys. Union, Part III, pp. 905-908, 1940.

The following references were received August 4, 1941, too late for insertion in appropriate place:

SNOW

(8) Conservation

H. T. Gisborne, How the wind blows in the forest of northern Idaho: Progress-report, Div. For. Protection, Northern Rocky Mountain For. and Range Exp. Sta., Mimeo., June 10, 1941.

PHYSICS OF SNOW AND ICE

M. I. Sumgin, Ice-crusts and ice-crusted hillocks, Priroda (Nature), No. 1, pp. 26-33, 1941 Russian).

Nevada Agricultural Experiment Station (C.E.),
Reno, Nevada
Blue Hill Meteorological Observatory (R.W.B. and L.J.),
Milton, Massachusetts

REPORT OF COMMITTEE ON GLACIERS, 1940-41

François E. Matthes, Chairman

(Published with the approval of the Director of the Geological Survey)

The personnel of the Committee is now as follows: Harry Fielding Reid, Professor Emeritus of Geology, Johns Hopkins University, 608 Cathedral Street, Baltimore, Maryland; William H. Hobbs, Professor Emeritus of Geology, University of Michigan, Ann Arbor, Michigan; Lawrence Martin, Chief of the Division of Maps, Library of Congress, Washington, D. C.; J. E. Church, Professor of Meteorology, Agricultural Experiment Station, University of Nevada, Reno, Nevada; Wm. Osgood Field, Jr., Explorer, 18 West Twelfth Street, New York, New York; Oliver Kehrlein, Chairman, Committee on Glacier Studies of Sierra Club, 1050 Mills Tower, 220 Bush Street, San Francisco, California; Kenneth N. Phillips, Associate Hydraulic Engineer, Water Resources Branch, United States Geological Survey, Chairman, Research Committee of the Mazamas, 606 Post-Office Building, Portland, Oregon; William S. Cooper, Professor of Botany, University of Minnesota, Minneapolis, Minnesota; Gerald Fitzgerald, Senior Topographic Engineer, Alaska Branch, United States Geological Survey, Washington, D. C.; Laurence M. Gould, Professor of Geology, Carleton College, Northfield, Minnesota; Dr. Max Demorest, Department of Geology, Yale University, New Haven, Connecticut; François E. Matthes (Chairman), Senior Geologist, Section of Glacial Geology, United States Geological Survey, Washington, D. C.

Dr. Otto Lütschg, President of the International Association of Scientific Hydrology, acting for its Executive Committee, has appointed Dr. Church President of the International Commission of Snow and Glaciers, and Mr. Matthes Secretary of that Commission, for the period 1939-42.

The following records of recession and shrinkage in volume of American glaciers were received from the field during the past year:

Glaciers of Mount Rainier, Washington

A report by FRED F. LAWRENCE, of the Conservation Branch of the United States Geological Survey, on the third resurvey of the lower Nisqually Glacier in 1940, shows that the terminus of that Glacier has receded 70 feet from the position it occupied in 1939 and 300 feet since the previous survey was made in 1936. The average annual recession during the past 22 years has been 72 feet, hence it appears that the general rate is being maintained essentially unchanged.

Recession-figures during the 22-year period have shown considerable departures from the mean, falling as low as 43 and 44 feet in some years and rising as high as 118 and even 155 feet in other years. A plot of the recession-figures made by the present writer, however, indicates no evidence of any cycles, and it can only be inferred that the departures from the mean are due to the various climatic factors that annually affect the economy of a glacier such as the Nisqually, which has a length of 4-1/2 miles and makes a descent of over 10,000 feet in altitude from the summit névés on the peak.

The original plan of repetitive surveys of the Nisqually Glacier, by the Geological Survey, in cooperation with the City of Tacoma Light Department (which depends for power upon the Nisqually River), called for remapping at intervals of five years. The first survey was made in 1931, the second in 1936, and the third was scheduled for 1941. However, so rapid has been the shrinkage of the Glacier during the last few years that it was decided to make the third survey in 1940.

In 1931 and 1936 the mapping was done on a scale of 1:4,800 with a contour-interval of 20 feet. It was soon found, however, that a smaller scale and larger contour-interval would afford sufficiently accurate data for the computations of loss of volume of the Glacier, and accordingly the 1940-survey was made on a scale of 1:96,000 and with a contour-interval of 50 feet. The stretch mapped in each case comprised the lower 10,000 feet of the ice-stream--that is, somewhat less than the lower half.

The longitudinal profiles based upon the successive surveys show that the Glacier's surface over a stretch of 3,000 feet was lowered by ablation from 30 to 60 feet during the five-year period 1931-36, and on an average somewhat more during the four-year period 1936-40. At the terminus, of course, the losses were still greater, averaging about 70 feet during each period. Since 1910, when the Glacier was mapped on a scale of 1:48,000 and with a contour-interval of 100 feet, in connection with the survey of the entire Mount Rainier National Park, the vertical losses over the 3,000-foot stretch before mentioned have averaged about 200 feet or about 6.6

feet per year. In the middle of the stretch the loss has been not less than 240 feet, or eight feet per year. It will be noted that during the period 1931-36, ablation proceeded at the rate of 6 to 12 feet per year; and during the period 1936-40 it reached a maximum of 15 feet per year.

Of peculiar interest is the fact that above the altitude of 5,600 feet the losses have been very variable. During the period 1931-36 the Glacier there actually increased in thickness from 10 to 40 feet, only to be reduced again 50 to 60 feet during the period 1936-40.

Without going into an account of the method adopted for the computation of losses in volume, it may be stated that the curves in Mr. Lawrence's report show that during the period 1910-31 the losses of ice in the surveyed portion of the Nisqually Glacier aggregated about 500 acre-feet per year; during the period 1931-36 they aggregated about 750 acre-feet per year; and during the period 1936-40 they aggregated not less than 3,400 acre-feet per year. These figures afford impressive testimony of the rapidly increasing reduction of the Nisqually's volume, which is not apparent from the constant rate of recession of its terminus.

Measurements by C. FRANK BROCKMAN, Park Naturalist of Mount Rainier National Park, on the Emmons Glacier, the largest ice-stream on Mount Rainier, show that it has receded 97 feet since the preceding year. This is considerably more than the average for the past decade. It is to be noted, however, that recession-measurements in the case of a glacier such as the Emmons, which ends in vast masses of stagnant, or partly stagnant ice thickly mantled by morainal débris, can hardly furnish more than approximate values. They serve nevertheless to indicate the general order of magnitude of the Glacier's recession from year to year, and it is to be hoped, therefore, that such measurements will continue to be made in the future.

The Carbon Glacier during the past year receded nearly twice as fast as at any time since measurements were begun. This ice-stream originates in a large cirque carved in the north flank of the peak, at an altitude of only 9,600 feet--that is, at a level nearly 5,000 feet below the summit. It is, however, fed in considerable measure by avalanches from the ice-cap on the summit platform. The lower end of the Glacier lies ensconced in a narrow, steep-walled gorge, and that circumstance probably accounts for the slowness of its recession as compared with the Nisqually and Emmons glaciers.

Year	Recession in feet	Year	Recession in feet
1936-37	20	1938-39	25
1937-38	18	1939-40	46

The South Tahoma Glacier, situated on the south-southwest side of Mount Rainier, also originates in a cirque but differs from the Carbon Glacier in that it receives no reinforcements by avalanching from the summit platform. It also showed a marked increase in the rate of its recession during the past year. Like the Emmons Glacier it is heavily encumbered at its lower end by morainal material released by ablation and therefore also presents difficulties for the determination of its recession. Three different reference points have been used by Mr. Brockman for his measurements. Here only the measurements from point B are recorded.

Year	Recession in feet	Year	Recession in feet
1936-37	13	1938-39	67
1937-38	76	1939-40	91

The Paradise Glacier is of peculiar interest because it does not originate high up on the flanks of Mount Rainier but occupies a gently sloping shelf at altitudes ranging from 6,300 to 7,200 feet. It is fed in large part by direct precipitation and wind drifting but doubtless receives considerable reinforcements also from the steeply sloping névé fields to the south of Anvil Rock. It is only 1-1/4 miles long and is often referred to as a "dead glacier." That appellation, however, is hardly justifiable, in view of the fact that there is, or has been until last year, enough movement in the mass to sustain three marginal lobes. The central one of these, commonly known as the Stevens Glacier, because it drains into Stevens Canyon, is now in truth dying, as it has become detached from the main mass. All that remains, according to Mr. Brockman, is a thin slab of ice about one-quarter mile long and separated from the main Glacier by 200 yards of bare rock.

The southern lobe of the Paradise Glacier, best known to the public because most readily accessible, receded but slowly during the past year, less, in fact, than during previous years. That fact is probably accounted for by the progressive thinning of the Glacier by ablation. No record of the reduction of its surface has been kept, but there is every reason to believe that the reduction is going on apace, in view of the southerly exposure of the Glacier, the absence of shadow-casting cliffs on either side, and the absence also of a protecting debris-cover. Following is the record of recession of the southern lobe.

Year	Recession in feet
1936-38 (2 years)	83
1938-39	75
1939-40	30

Significant in connection with the foregoing records of glacier-recession are the meteorologic data which Mr. Brockman appends to his report: The snow-precipitation during the winter of 1939-40, as recorded in Paradise Valley, at an altitude of 5,557 feet, amounted to only 402 inches as compared with a normal fall of 625 inches. Mean temperatures during the past year were about 18 per cent above the average.

Glaciers of Mount Hood, Oregon

The Research Committee of the Mazamas, of Portland, Oregon, according to the report of KENNETH N. PHILLIPS, Chairman, on September 21, 1940, revisited the Eliot Glacier, the largest ice-stream on Mount Hood, and by tape-measurement determined its recession since September 24, 1939, to be 18 feet. In view of the fact that temperatures during the period July, 1939, to September, 1940, had been decidedly above normal for each month, and that the snowfall on Mount Hood had been very slight during October and November, and until December 8, 1939, it was expected that the recession of the Eliot Glacier would be much more than 18 feet, "perhaps even more than the 64-foot retreat observed in 1938-39". The relatively slight change in the length of the Glacier, therefore, seemed difficult to account for with the data at hand. "However," suggests Mr. Phillips, "it seems possible that the forward movement of the Glacier during the year was considerably greater than normal owing to the warm weather, thus compensating largely for the greater ablation by melting and evaporation."

The party, further, took the first steps toward determining the rate at which the Glacier's surface is being lowered by ablation from year to year, by running two transit-stadia profiles across it and marking the end points thereof on the lateral moraines. The lower line is situated about 300 feet above the beginning of the terminal face of the Glacier, the upper line about one-quarter mile farther upstream. The two profiles will be resurveyed at intervals of two or three years to determine the vertical losses by ablation.

Cryocinemeter measurements were made on September 21-22, 1940, to determine the rate of advance of the terminus in autumn weather. Over a period of 23 hours, 45 minutes, the total advance observed was 0.482 inch, a rate of 0.487 inch per day. The temperature during the period of observation ranged from about 40° to 60° F.

The Research Committee also continued its recently inaugurated program of recording temperatures on the summit of Mount Hood with maximum and minimum thermometers. The minimum recorded for the winter of 1939-40 was -6° F (probably higher than the true minimum, as the thermometer-box had become covered with several feet of snow). The maximum, recorded on August 20, 1940, was 69° F.

The remnants of an ancient forest of large trees that once grew on the flanks of Mount Hood at altitudes as high as 7,500 feet--that is, considerably above the present timber-line for large trees--were briefly examined by Professor DONALD B. LAWRENCE, of the University of Minnesota, and Mr. Phillips. These remnants are situated in the valley of White River, which is cut in the south flank of the peak, and they probably are the same which A. H. Sylvester of the United States Geological Survey discovered in 1906, when he was making the topographic map of Mount Hood and its vicinity. The interest that attaches to them is that they may indicate a relatively recent period of mild, rainy climate during which the timber-line lay at a much higher level than at present.

As was mentioned in the first annual report of the Committee on Glaciers [Trans. Amer. Geophys. Union, Thirteenth Annual Meeting, pp. 282-287, 1932; this reference on p. 286] remnants of another ancient forest--the Stadter Buried Forest--were found in 1926 by a party of Mazamas, while on a climb near the timber-line on the southwest slope of Mount Hood. These remnants consist of long, straight trunks lying in a tangled mass beneath what is believed to be a recent moraine of the Zigzag Glacier, and they are being exposed to view by the incision of a new stream-cut gully.

The rings of growth in those ancient trees average about 18 to 20 to the inch--that is, they are about the size of the rings in trees such as grow today about the base of Mount Hood. The rings in timber-line trees, by contrast, average more nearly 100 to the inch. There is good reason to believe, therefore, that the ancient forest grew high up on the slopes of Mount Hood at a time when, because of milder climate, the timber-line lay at least a thousand feet higher than it does at present. Now that the occurrence of a period of warmer climate than the present during the middle third of the Post-Pleistocene interval is definitely established by several independent lines of evidence, in Europe as well as in North America and in New Zealand, these ancient "buried forests" at high levels on Mount Hood gain new significance, and it seems well worth while to investigate them with care, in order to determine, if possible, whether they date back to the "climatic optimum" of the Post-Pleistocene interval.

Glaciers of the Sierra Nevada, California

The report by M. E. BEATTY, Acting Park Naturalist of Yosemite National Park, gives the results of measurements both of recession and of reduction of surface for several glaciers.

The toe of the East Lyell Glacier on October 4, 1940, was still covered with snow, hence no recession-measurement could be made. Reduction of the surface of the Glacier by ablation, on the other hand, was determined at two points on a profile across the middle of the Glacier that had been established in 1933. At Station 1, 504 feet from the west end of the base-line, there was a vertical loss of 4.4 feet since 1939, and at Station 2, 768 feet out, the vertical loss was 6.8 feet. At Station 1, the total loss in seven years amounted to 22.3 feet; at Station 2 it amounted to 38.8 feet. The mean annual loss for the seven-year period, therefore, was 3.2 feet at Station 1, and 5.6 feet at Station 2. Assuming that the Glacier has a maximum thickness in its cirque of about 300 feet, it will, at the present rate of melting, cease to exist in about 50 years.

A measurement to the front of the West Lyell Glacier showed a recession since the previous year of three feet. What is more significant, however, is that measurements with an Abney level to two points on a profile across the Glacier established in 1933 showed a lowering of the surface by ablation closely similar to that on the East Lyell Glacier. At Station 1, 311 feet distant from the west margin, the vertical loss since 1939 proved to be 2.8 feet; at Station 2, 714 feet distant, the vertical loss was 6.3 feet. During the seven-year period since 1933 the surface of the Glacier was lowered 17.2 feet at Station 1, and 26.4 feet at Station 2. The mean annual vertical loss for the seven-year period, therefore, was 2.5 feet at Station 1, and 3.8 feet at Station 2.

The Maclure Glacier in 1940 showed but little change in appearance since 1939. No measurement of recession was possible, owing to the large "cave-in" that had taken place at its front in what supposedly was morainal material, but what proved to be moraine-covered glacier-ice. The cave-in was due, of course, to the melting out of a cavern in the ice by a stream issuing from the base of the Glacier.

Measurements to the broad front of the Dana Glacier could be made only at two points. At Station 3 the ice had receded 30 feet since 1939; at Station 6 there had been a recession of not less than 64 feet.

Glaciers of Glacier National Park, Montana

JAMES L. DYSON, during the summer of 1940, visited six of the larger glaciers of Glacier National Park and found them all in a state of accelerated recession. The winter of 1939-40, he reports, was one of the most open winters on record in that part of the Rocky Mountains. The snowfall was so light that the roads into some of the higher areas were passable throughout the greater part of the winter. That fact, coupled with a prolonged period of high temperatures during the ensuing summer, resulted in an unusually great diminution of the glaciers in the Park. From some glaciers all of the snow that fell during the winter of 1939-40 was completely removed, and from most of the smaller ice-bodies the compacted névé of several preceding winters was removed also.

Measurements to the front of the Grinnell Glacier showed that the recession during the summer of 1940 alone (up to September 6, 1940) amounted to more than 39 feet, whereas the previous recession since August, 1937, had been only 26 feet. Mr. Dyson's measurements are as follows.

Dates	Interval	Recession
August 29, 1937 to July 27, 1939	1 year, 11 months	20 feet
July 27, 1939 to July 3, 1940	11 months	6 feet
July 3, 1940 to August 11, 1940	1 month	18 feet
August 11, 1940 to September 6, 1940	1 month	21 feet
Total in 3 years		65 feet

The detailed map of the Sperry Glacier, which Mr. Dyson made for the National Park Service in 1939, showed a projecting ice-mass 700 feet long and from 200 to 600 feet in width, on the west side of the main body of the Glacier. All of this projection had disappeared late in August, 1940.

The Chaney Glacier appeared to have been reduced 8 to 10 feet in thickness.

The Shepard Glacier, which around the beginning of the present century rested on two rock shelves separated by a vertical cliff that was exposed only at the northern end of the ice-mass, in 1940 was confined largely to the upper shelf, and had been reduced to less than one-half its former surface area.

The Agassiz Glacier, which in 1900 covered an area of about 1.40 square miles and was one of the two largest and most spectacular glaciers in the Park, in 1940 had been reduced to two disconnected masses of stagnant ice aggregating together no more than 0.29 square mile. Whereas in 1900, to judge by the position of the fresh terminal moraine, it probably had a thickness of several hundred feet, the two remaining masses appear to be not over 35 feet thick. It is clear that, if the present climatic trend continues, the Agassiz Glacier--named for the father of glaciology--will cease to exist in only a very few years.

The glacieret at Iceberg Lake, which as late as 1920 still extended a considerable distance out into the Lake and had a frontal cliff 90 to 100 feet high, from which icebergs calved off from time to time, in 1940 had melted back from the border of the Lake and ceased to produce the icebergs which heretofore were an object of interest to the visiting public.

Mr. Dyson also had opportunity to visit the Grant Glacier on the Flathead Range, to the south of Glacier National Park. It appeared wholly divested of snow in the summer of 1940, and, to judge from its relation to the fresh moraine, which it probably touched in 1900, it is now only about one-half as large as it then was.

Glaciers of the Wind River Range, Wyoming

To FLOYD WILSON, of Burris, Wyoming, the Committee is indebted for information on the recession of the principal glaciers of the Dinwoodie Group, near Gannett Peak. All of these glaciers are in recession and evidently have been for a number of years. Markers were set only below the Gannett Glacier and its branches, and as a consequence figures of recession can be given for these only. The main Gannett Glacier, according to Mr. Wilson's measurements, receded not less than 102 feet during the summer of 1940. The middle fork of the Glacier receded 87 feet. The south fork, he estimates, must have receded about 500 feet in the last five years.

Glaciers of Rocky Mountain National Park, Colorado

H. R. GREGG, Park Naturalist of Rocky Mountain National Park, has continued to make measurements of the recession of the Andrews and Tyndall glaciers. These belong, both of them, in the "vestigial" class and for that reason are of unusual interest. Both are steeply sloping masses of laminated ice situated in relatively small cirques on the east side of the Continental Divide. The recession of these glacierets amounts to only a few feet per year and in some years is not measurable because of accumulations of snow on the terminus. Apparently, because of their sheltered positions, both of these glacierets suffer less, proportionately, from the increasing dryness and warmth of the climate, than the much larger glaciers in Glacier National Park and in the Pacific Northwest.

Glaciers of Mount McKinley National Park, Alaska

FRANK T. BEEN, Superintendent of Mount McKinley National Park, reports that he has at last succeeded in obtaining a measure of the recession of the Sunset Glacier. It had receded 12 feet since the summer of 1939.

Difficulty has been experienced during past years in measuring the recession of the East Fork and Toklat glaciers, partly owing to inclement weather, partly because the monuments built for reference-points are frequently washed away by floods. It is reasonably certain, however, that all of these glaciers on the Alaska Range are in a state of recession.

U. S. Geological Survey,
Washington, D. C.

REPORT OF ADVISORY COMMITTEE ON SOIL CONSERVATION RESEARCH, 1940-41

R. E. Horton, Chairman

(Presented by title)

The membership of the Committee has remained unchanged during the past year and consists of J. E. Church, W. W. Horner, A. F. Meyer, Caleb M. Saville, L. K. Sherman, Samuel Shulits, Roy N. Towl, F. J. Veihmeyer, and Robert E. Horton (Chairman).

As heretofore, active work is performed chiefly by the Executive Sub-Committee consisting of Messrs. Horner, Sherman, and Horton. It happens that during most of the past year the members of the Executive Sub-Committee have been acting in a distinct capacity as Consultants on Flood Control of the Department of Agriculture. This has occasioned frequent visits to Washington and numerous discussions of research work of the Department of Agriculture, both in connection with the Soil Conservation Service and the Forest Service. Also the Executive Sub-Committee attended the Infiltration School conducted jointly by representatives of the Flood Control Division, Forest Service, and Research Division of the Department of Agriculture, at Asheville, North Carolina, in July, 1940.

These things have given members of the Committee an opportunity to analyze and apply numerous examples of hydrologic data in relation to flood-control problems and so to learn more specifically the requirements of the United States Department of Agriculture for hydrologic research. This involved the analysis and interpretation of many hundreds of infiltrometer-experiments, hundreds of permanent-plat experiments and a large number of individual storms on experimental drainage-basins. These studies by members of the Committee serve also as pilot-studies to determine what data are needful to be obtained to make a given experiment complete, and how they should be collected and analyzed. This field of research is so completely new that, needless to say, members of the Committee have themselves learned many things. It is the hope of the Chairman of the Committee that with this background the Committee may during the coming year participate more actively in the collection and analysis of hydrologic research data by the Soil Conservation Service.

It seems unavoidable that there should be a long lag interval between conception and accomplishment in research work by governmental agencies. Thus it happens that some matters strongly urged by this Committee in the past are only now coming to fruition, though not always through the channels originally anticipated. Among early recommendations of this Committee were:

(1) That arrangements be made for publication in some form of hourly rainfall-records collected in the past by regular United States Weather Bureau stations, so that these data might be made available for use in connection both with the research work and flood-control work of the Soil Conservation Service. It is the understanding of the Chairman that this is to be done through the Hydrologic Division of the United States Weather Bureau under direction of Merrill Bernard.

(2) Another early recommendation was for collection of data and research work on hydrologic conditions in winter, particularly with snow-cover and ground-frost, both as to infiltration through frozen soil and as to the effect of snow-cover on floods. It is understood that systematic collection of frost-penetration and snow-cover and other pertinent data has been undertaken at the research stations of the Soil Conservation Service; also a hydrologic station for study of the effect of snow-cover and ground-frost on runoff has been established at Michigan State Experiment Station, East Lansing, under the direction of W. U. Garstka of the Soil Conservation Service, Research Division.

One other recommendation of the Committee in this connection, that of carrying out infiltrometer-experiments on frozen soils, has not yet been undertaken. It is again urged that this be done.

The Research Committee has strongly urged publication in some form of the results of hydrologic researches by the United States Department of Agriculture, including not only those of the Soil Conservation Service but of the Forest Service as well. This should be publication of original data in some form such that they may be available in limited editions at least, with sufficient completeness so that any one may use or analyze them for any purposes which they legitimately serve. Something has been accomplished along this line through the publication, by processing, of many volumes of the results of runoff-experiments of the Soil Conservation Service, Research Division, on small drainage-basins. Much, however, remains to be desired in the matter of publication of original data. Publication of the extensive results obtained from permanent-plot experiments both of the Soil Conservation Service and the Forest Service still lags.

Provision should also be made for publication of the results of field infiltrometer-experiments. There has been some excuse in the past for delay in this because the procedure is new and the methodology of analysis and interpretation is still in the course of development. During the past year the Executive Sub-Committee has outlined procedures for tabulation and publication of such data.

In connection with this matter of publication of hydrologic data collected by governmental agencies there is something more to be said. Hydrologic research by a governmental agency is usually undertaken with an objective. If not it would often be difficult to secure appropriations for research. The data are turned over to some one for analysis in line of duty. Under the restrictions of Department and Civil Service regulations this job does not always fall to the men best qualified by training in hydrophysics and experience in hydrologic research. When the analysis is completed, it often happens that only the final results and conclusions are published. This does not meet the requirements of hydrologic science. Regardless of the manner of use of such data by the particular governmental agency which collected the data, there should be publication of the original data in some form, sufficiently complete so that any one may use them for any purpose which they will serve. A limited edition in mimeographed or other processed form would meet this important requirement.

The Advisory Committee on Research was appointed in 1938 at the request of Dr. W. C. Lowdermilk, then Chief of the Division of Research of the Soil Conservation Service. The members of the Committee then realized the difficulties of the task before them, and any one familiar with the ramifications of governmental agencies could not have expected 100 per cent accomplishment. Some of the Committee's recommendations, although approved and even definitely assigned to personnel, have fallen by the wayside. This has been due to various causes, such as changes of personnel, reorganizations, shifting of allotments to meet requirements of budget, and, regrettably, sometimes it has been due to lack of suitable personnel to carry out the work.

One function of the report of the Committee is to tell what it has accomplished. From the nature of its work, this is difficult in the present instance. In order, however, to give something definite, the Chairman has estimated that the Committee has accomplished at least 50 per cent of what it has undertaken and that this percentage is likely to increase as the work goes on.

Finally, acknowledgment is made to Dr. M. L. Nichols, Chief of the Division of Research of the Soil Conservation Service, for his cordial cooperation with the Committee in its work.

Voorheesville, New York

SUPPLEMENT

M. L. Nichols

The following information regarding research and publication in matters relating to runoff in which the Advisory Committee has taken an active part has been furnished by Dr. M. L. Nichols (by letter). Dr. Nichols states: "With reference to the publication of original hydrologic data I feel that we are making excellent progress. During the past year mimeographed editions of hydrologic data collected at the original soil-erosion experiment stations at Spur, Texas, Hays, Kansas, Guthrie, Oklahoma, and Clarinda, Iowa, were published for field-distribution. Also bulletins of hydrologic data for the year 1939 for experimental watersheds at Coshocton, Ohio, and Waco, Texas, are in the hands of the printer. The bulletin of hydrologic data for the years 1938-40 for the experimental watershed at Hastings, Nebraska, and for the year 1940 for the experimental watershed at Coshocton, Ohio, have been completed and have been forwarded through the Editorial Department for publication.

"These publications contain a large amount of basic hydrologic data in a form sufficiently complete to satisfy the needs of hydrologists in many fields of activity in addition to that of soil- and water-conservation. It is planned to continue the annual publication of the basic hydrologic data and it is hoped that in the near future it will be possible to publish annually basic data collected at all of our field-stations for wide distribution to hydrologists and others having use for such data."

REPORT OF COMMITTEE ON RUNOFF, 1940-41

W. G. Hoyt, Chairman

The Committee members are the same as last year, namely: H. K. Barrows; Merrill Bernard; E. S. Cullings; R. S. Goodridge; G. A. Hathaway; Joseph Jacobs; F. T. Mavis; H. S. Riesbol; Waldo E. Smith; F. F. Snyder; and H. G. Wilm.

During the year one addition was made, namely, AURELIO BENASSINI of Mexico City and associated with the Mexican Government. One of Mr. Benassini's associates, Mr. Quintero, was appointed on Mr. Bernard's Rainfall Committee, and in view of the fact that we have common hydrologic problems with Mexico, it seems desirable to have representatives of the Mexican Government on both the Rainfall and the Runoff Committees.

Runoff during year, May 1940 to April 1941--Heretofore as a part of the report of the Runoff Committee I have not discussed runoff as a current phenomenon on a national basis. It may be desirable to outline some of the high points with respect thereto.

In general we may say that the 12 months now ending were probably below normal with respect to the number and magnitude of flood-occurrences when compared to the last ten-year period. The most wide-spread floods in which numerous records of runoff were broken during the past 12 months seem to have been associated with storms during August which were especially heavy in eastern Tennessee, western North Carolina, Virginia, northern Georgia, and northern South Carolina. In central Oklahoma in August and in east Texas during late November and early December, 1940, unusually heavy rains resulted in flood-runoff exceeding prior records on several streams. During February, 1940, floods were general throughout the Sacramento River Valley, California.

Beginning last summer, however, and continuing through to the present, persistent rains throughout the Southwest from Texas to California have, through recharge to ground-water and replenishment of soil-moisture, been of untold benefit in parts of these areas where critical water-shortages were prevalent. Although these unusual rains in the Southwest have not resulted in unusual floods, the total volume of runoff in many areas has exceeded that for many years past.

In contrast, continued deficiencies in precipitation for over six months throughout the East-Central States are leading toward a serious drought with respect to surface and ground-water supplies in these areas. The total runoff since October 1 for a 280,000 square-mile area generally coincident with the lower Ohio River Basin has averaged only 35 per cent of the median.

Research during the year--In continuation of an effort to determine the intricate relations between rainfall, runoff, soil-moisture, and soil-movement under different climatic, physiographic, and geologic conditions and the effect of cover and land-use on such relationships, some 125 experimental areas, watersheds, forests, or demonstration-projects are being maintained by the various Federal agencies and more especially by the Soil Conservation Service and the Forest Service. Through the hearty cooperation of G. W. MUSGRAVE and J. M. DAVIDSON, Research Division, Soil Conservation Service, I. H. SIMS, Division of Forest Influences, Forest Service, MERRILL BERNARD, Weather Bureau, GAIL HATHAWAY, United States Engineer Department, and others, a compilation has been made of each experimental area. As a part of the report of the Runoff Committee there is attached Appendix A showing alphabetically, by States, (a) the name of the research area and nearest town, (b) date of establishment, (c) the mailing address for inquiries relating to the research project, (d) the plant-cover or land-use, (e) the number and size of watershed-units, runoff-plots, terraces, and lysimeters, (f) the number of recording and nonrecording rain-gages, and (g) a statement indicating whether or not the following phenomena are being observed, namely, air-temperature, wind-movement, evaporation, soil-temperature, soil-freezing, snow-cover, ground-water levels, soil-moisture, soil-loss, suspended load, sedimentation-surveys, and chemical quality. It is hoped that eventually the material contained in this Appendix can be included in a manual to be prepared by the same informal committee showing rather specifically the principal Federal sources of hydrologic data, and the availability thereof.

The following research projects and office studies relating to runoff have come to the attention of the Chairman:

Dr. WILM of the Rocky Mountain Forest and Range Experiment Station, with headquarters at Fort Collins, Colorado, reports that in addition to their current research on the Manitou and Fraser Experimental Forests an investigation is under way to determine rainfall-runoff relations for typical basins draining the Rocky Mountain front range. To date stream-flow of Goose Creek, North Fork of South Platte, Middle Boulder Creek, and Big Thompson River have been correlated with available precipitation-records. It is hoped to extend these studies to include all the drainages in the main range of the Rocky Mountains. Results of the analyses to date are to be published.

Mr. Cullings of the Black River Regulating District, Watertown, New York, reports continuation of rainfall-runoff studies in the Black River Drainage-Basin in New York with special reference to flood-runoff during the spring. Studies are being made to determine the contributions to flood-runoff of snow-melt influenced by temperature alone and also associated with rain.

Mr. Bernard and Mr. Snyder of the United States Weather Bureau report that in connection with their studies of forecasting runoff from melting snow, considerable research work is being carried on in Yellowstone Park and on Cottonwood Creek, Utah, the objective of which is to develop correlation of meteorological factors affecting snow-melt. Progress is also being made by the Weather Bureau in cooperative studies with the United States Corps of Engineers under which heat transferred through atmospheric turbulence is considered to be the most significant factor. The Weather Bureau is continuing its development of stream-flow forecasting methods and have been successful in injecting into forecasting methods a practical utilization of rationalized rainfall-runoff relationships identified with modern applied hydrology. Existing forecasting methods for the Merrimac, Connecticut, Susquehanna, Potomac, upper Ohio, and Kanawha river-basins have been extended, and studies are being made currently for tributaries of the Colorado River in Texas.

Mr. Hathaway of the United States Engineer Department reports rainfall-runoff studies being conducted in several of the district offices of the Corps of Engineers to determine rainfall-runoff relationships with special reference to determination of peak-discharges. As an adjunct thereto one experimental area, somewhat similar to the experimental areas maintained by the Forest Service and the Soil Conservation Service, has been established at Vicksburg, Mississippi.

Projects in which the Geological Survey is interested include:

A cooperative Work Projects Administration study sponsored by the Weather Bureau and the Survey to determine in detail the physiographic characteristics of all of the drainage-basins and minor subdivisions thereof for which topographic maps are available and stream-gaging stations in operation throughout the northeastern part of the United States. This project was completed June 30, 1940, and it is hoped that basic data as follows will be eventually published in a water-supply paper: (a) Drainage-area; (b) stream-density; (c) volume-form factor; (d) land-slope east-west, north-south, and average; (e) channel-slopes of principal streams; (h) land-elevation, maximum, mean and minimum; (i) area of water-surface in lakes and reservoirs. The availability of such data will allow engineers and research workers to analyze the relations between stream-flow characteristics and basin-characteristics.

The beginning of a Work Projects Administration study under the sponsorship of the Weather Bureau and the Survey of the total runoff during the five major winter floods and the five major non-winter floods for the period of record at all of the gaging stations in the United States, the study to show the runoff for each day and accumulated runoff for the ten days preceding and 15 days following the peak. (This study is a continuation and enlargement of the private study undertaken by Frederick H. Fowler, Consulting Civil Engineer, San Francisco, and President, American Society of Civil Engineers.)

A study of flood-characteristics in New Jersey carried on jointly by the New Jersey Water Policy Commission and the Survey.

A study of flood-characteristics in Massachusetts carried on jointly by the Department of Public Works and the Survey.

In November, 1940, the Survey initiated a program of issuing monthly reports on stream-flow conditions based on reports from representative gaging stations throughout the country. These reports review the fluctuations in stream-flow and delineate the areas of deficient and excessive stream-flow in terms of normal.

U. S. Geological Survey,
Washington, D. C.

APPENDIX A--SUMMARY OF HYDROLOGIC RESEARCH DATA BEING COLLECTED AT EXPERIMENTAL AREAS, WATERSHEDS, FORESTS, AND DEMONSTRATION-PROJECTS MAINTAINED BY FEDERAL AGENCIES

(Compilation by W. G. Hoyt, Geological Survey, in cooperation with J. M. Davidson, Research Division, Soil Conservation Service, I. H. Sims, Division of Forest Influences, Forest Service, Merrill Bernard, Weather Bureau, and Gail A. Hathaway, United States Engineer Department, and others)

PREFACE

The arrangement of the compilation is alphabetical by States and nearest town followed by the name of the area; date work was initiated; address to which inquiries should be directed (this information also identifies the organization maintaining the area); type of cover; land-use, and in some instances total area; number and range in size of watershed-units, plots, terraces, and lysimeters from which runoff is measured; number of recording and non-recording raingages and statements as to whether or not information regarding the following phenomena are being collected: Air-temperature, wind-movement, evaporation, soil-temperature, soil-freezing, snow-cover, ground-water levels, soil-moisture, soil-loss, suspended load, sedimentation-surveys, and chemical quality. In a few instances the compiler of the data indicated that the results of the observations are published. In all such instances the word "published" has been included in parenthesis in the compilation.

ALABAMA

Center Star: Lauderdale County Area; March, 1941; address inquiries to A. S. Fry, Head Hydraulic Engineer, Tennessee Valley Authority, 705 Union Building, Knoxville, Tennessee; land-use--agriculture and pasture; runoff measured from one 100-acre watershed; rainfall measured at one recording and one non-recording gage; observations also made of ground-water levels and suspended load including sedimentation-surveys.

ARIZONA

Globe: Sierra Ancha Experimental Forest; May, 1932; address inquiries to Director, Southwestern Forest and Range Experiment Station, United States Forest Service, Tucson, Arizona; plant-cover--grass-chaparral, open timber, ponderosa pine-fir forest; area--13,255 acres, runoff measured from 11 watershed-units ranging in size from 9 to 2,400 acres; eight plots ranging in size from 0.02 to 0.25 acre and 35 lysimeters ranging in size up to 1/3 acre; rainfall measured at 27 recording and 68 non-recording gages; observations also made of air-temperature, wind-movement, evaporation, soil-temperature, soil-freezing, snow-cover, soil-moisture, and soil-loss.

Globe: Summit Work Center; 1931; address inquiries to Director, Southwestern Forest and Range Experiment Station, United States Forest Service, Tucson, Arizona; plant-cover--semi-desert shrub and chaparral; runoff measured from nine plots ranging in size from 0.25 acre to 1.25 acres and eight lysimeters of approximately 1/10,000 acre; rainfall measured at one recording and six non-recording gages; measurements also made of soil-loss.

Safford: Safford Demonstration Area; August, 1938; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; runoff measured from six watershed-units of range-land ranging in size from 349 to 764 acres; rainfall measured at 18 recording and 18 non-recording gages; observations also made of air-temperature and relative humidity.

Duncan and Safford: Southeastern Arizona Range and Farm Lands; November, 1937; address inquiries to Project Supervisor, Soil Conservation Service, Box 4096, University Station, Tucson, Arizona; runoff and infiltration measured semi-annually from five small duplicate grazing plots; rainfall measured at 14 recording and 18 non-recording gages; measurements of soil-moisture also made.

ARKANSAS

Batesville: Livestock and Forestry Branch Experiment Station, University of Arkansas; April, 1939; address inquiries to Project Supervisor, Soil Conservation Service, Fayetteville, Arkansas; runoff and soil-loss measured from 12 plots of cotton, kudzu, and grain ranging in size from 1/5 to 7/8 acre; rainfall observed at five recording and five non-recording gages.

Bentonville: Soil Conservation Demonstration Area; September, 1938; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; runoff measured from six watershed-units of cultivated, pasture, wooded, strip-cropped or terraced land ranging in size from 9.34 to 24.0 acres; rainfall measured at six recording and six non-recording gages; observations also made of air-temperature, relative humidity, and soil-temperature.

Mena: Irons Fork Experimental Forest; August, 1936; address inquiries to Director, Southern Forest Experiment Station, United States Forest Service, Federal Office Building, New Orleans, Louisiana; plant-cover--virgin and second growth shortleaf pine-hardwood; area--8,878 acres; runoff measured from four watershed-units ranging in size from 107 to 195

ARKANSAS--Concluded

acres; 67 plots ranging in size from 0.0065 to 0.01 acre, and one installation of spreaders and diversion-trenches, area 180 acres; rainfall measured at two recording and 86 non-recording gages; observations also made of air-temperature, evaporation, soil-temperature, ground-water levels, soil-moisture, and soil-loss.

CALIFORNIA

Berkeley: Strawberry Canyon Plots; 1931; address inquiries to Director, California Forest and Range Experiment Station, United States Forest Service, 330 Giannini Hall, Berkeley, California; plant-cover--chaparral; runoff and soil-loss measured from six plots, 1/16 acre each; rainfall measured at one recording and two non-recording gages.

Fresno: Kings River Work Center; October, 1936; address inquiries to Director, California Forest and Range Experiment Station, United States Forest Service, 330 Giannini Hall, Berkeley, California; plant-cover--grass, woodland, pine-fir forest; area--1,773 acres; runoff measured from ten watershed-units ranging in size from 9 to 548 acres; rainfall measured at three recording and 102 non-recording gages; observations also made of air-temperature, wind-movement, snow-cover, soil-loss, and suspended load.

Glendora: San Dimas Experimental Forest; March, 1934; address inquiries to Director, California Forest and Range Experiment Station, United States Forest Service, 330 Giannini Hall, Berkeley, California; plant-cover--chaparral; area--18,400 acres; runoff measured from 17 watershed-units ranging in size from 35 to 10,250 acres; 22 plots, each 0.025 acre; rainfall measured at 15 recording and 276 non-recording gages; observations also made of air-temperature, wind-movement, evaporation, soil-temperature, soil-moisture, soil-loss, and suspended load.

North Fork: North Fork Work Center; 1929; address inquiries to Director, California Forest and Range Experiment Station, United States Forest Service, 330 Giannini Hall, Berkeley, California; plant-cover--chaparral, woodland brush, ponderosa pine; runoff measured from 16 plots ranging in size from 0.01 to 0.025 acre; rainfall measured at three recording and five non-recording gages; observations also made of air-temperature, wind-movement, soil-moisture, and soil-loss.

O'Neals: San Joaquin Experimental Range; May, 1936; address inquiries to Director, California Forest and Range Experiment Station, United States Forest Service, 330 Giannini Hall, Berkeley, California; plant-cover--grass; area--3,650 acres; runoff and soil-loss measured at nine plots, 0.025 acre each; rainfall observed at one recording and one non-recording gage.

Santa Paula: Soil Conservation Demonstration Area; October, 1938; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; runoff measured from five watershed-units with cultivated or native cover ranging in size from 44.4 to 413 acres; rainfall measured at 12 recording and 12 non-recording gages; observations also made of air-temperature, relative humidity, and soil-temperature.

Somis: Winter fallow-belt, Somis Experimental Farm; November, 1938; address inquiries to Project Supervisor, Soil Conservation Service, Santa Paula, California; rainfall measured at one recording and two non-recording gages; observations also made of soil-temperature and soil-moisture under specialized farming.

Watsonville: Soil Conservation Service Demonstration Area; October, 1938; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; runoff measured from four watershed-units of pasture and orchard-land ranging in size from 10.1 to 27.4 acres; rainfall measured at eight recording and eight non-recording gages; observations also made of air-temperature, relative humidity, and soil-temperature.

COLORADO

Cheyenne Wells: Central Great Plains Area; July, 1938; address inquiries to Project Supervisor, Soil Conservation Service, Cheyenne Wells, Colorado; rainfall measured at two recording gages and soil-moisture observations made under grazing-land use.

Falcon: Soil Conservation Demonstration Area; May, 1938; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; runoff measured from four watershed-units of cultivated and range-land ranging in size from 10.6 to 39.7 acres; rainfall measured at eight recording and eight non-recording rain-gages; observations also made of air-temperature, relative humidity, soil-temperature, and soil-moisture.

Fraser: Fraser Experimental Forest; August, 1937; address inquiries to Director, Rocky Mountain Forest and Range Experiment Station, United States Forest Service, Ft. Collins, Colorado; plant-cover--lodgepole pine and Engelmann spruce; area--17,000 acres; runoff measured from one watershed-unit of 700 acres; rainfall measured at one recording and 100 non-recording gages; observations also made of air-temperature, wind-movement, evaporation, snow-cover, ground-water levels, and soil-moisture.

Woodland Park: Manitou Experimental Forest; 1938; address inquiries to Director, Rocky Mountain Forest and Range Experiment Station, United States Forest Service, Ft. Collins, Colorado; plant-cover--grass and young ponderosa-pine; runoff measured from 11 watershed-units

COLORADO--Concluded

ranging in size from 0.3 acre to 4,500 acres; 12 plots of 0.01 acre each, and 18 lysimeters, each 1/10,000 acre; rainfall measured at five recording and more than 48 non-recording gages; observations also made of air-temperature, wind-movement, evaporation, ground-water levels, soil-moisture, and soil-loss.

GEORGIA

Americus: Soil Conservation Service Demonstration Area; July, 1938; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; runoff measured from four watershed-units of cultivated land, three of which are terraced, ranging in size from 23.5 to 59.2 acres; rainfall measured at six recording and six non-recording gages; observations also made of air-temperature, relative humidity, and soil-temperature.

Watkinsville: Southern Piedmont Experiment Station; January, 1937; address inquiries to Project Supervisor, Soil Conservation Service, Watkinsville, Georgia; runoff and soil-loss measured from 42 plots ranging in size from 1/60 to 1/20 acre; rainfall measured at 14 recording and 50 non-recording gages; effects of straw- and hay-mulches (published) and of contour-balk system of farming; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C., concerning runoff-measurements on watershed-unit of 19.2 acres of land under two-year rotation of small grain-hay-cotton; established September, 1939.

IDAHO

Emmett: Soil Conservation Service Demonstration Area; August, 1938; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; runoff measured from two watershed-units of range-land, ranging in size from 69.4 to 219.4 acres; rainfall measured at four recording and four non-recording gages; observations also made of air-temperature, relative humidity, and soil-temperature.

Idaho City: Boise Basin Branch and Arrowrock Substation; June, 1933; address inquiries to Director, Intermountain Forest and Range Experiment Station, United States Forest Service, Forest Service Building, Ogden, Utah; plant-cover--bunchgrass and other range on granitic soils; area--5,352 acres; runoff measured from five watershed units ranging in size from 10 to 200 acres and six lysimeters, 1/500 acre each; rainfall measured at three recording and 54 non-recording gages; observations also made of air-temperature, wind-movement, snow-cover, soil-moisture, and soil-loss.

Moscow: Idaho Agricultural Experiment Station; October, 1937; address inquiries to Project Supervisor, Soil Conservation Service, Pullman, Washington; measurements being made of soil- and water-losses from six small plots to determine effect of additions of organic matter to soil on erosion, runoff, and soil-structure.

Moscow: Soil Conservation Service Demonstration Area; November, 1937; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; runoff measured from two watershed-units of cultivated land, ranging in size from 146.8 to 177.9 acres; rainfall measured at two recording and two non-recording gages; observations also made of air-temperature, relative humidity, and soil-temperature.

Southeast Idaho: Tetonia Substation of Idaho Agricultural Experiment Station; March, 1939; address inquiries to Project Supervisor, Soil Conservation Service, Aberdeen, Idaho; general land-use--winter wheat-fallow; rainfall measurements made at one recording and one non-recording gage; observations also made of soil-freezing, soil-moisture, and soil-loss, and of the effects of various types of tillage.

ILLINOIS

Dixon Springs: Soil and Water Conservation Experiment Station; 1937; address inquiries to Project Supervisor, Soil Conservation Service, Box 37, Urbana, Illinois; runoff and soil-loss measured from 29 plots of farming land ranging in size from 1/50 to 1/5 acre; rainfall measured at six recording and 16 non-recording gages. Published.

Edwardsville: Soil Conservation Service Demonstration Area; March, 1938; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; runoff measured from four watershed-units of cultivated and pasture-land ranging in size from 12.55 to 289.8 acres, of which the 12.55-acre watershed is terraced; rainfall measured at eight recording and eight non-recording gages; observations also made of air-temperature, relative humidity, and soil-temperature.

Urbana: Illinois Agricultural Experiment Station, Animal Husbandry Farm; 1938; address inquiries to Project Supervisor, Soil Conservation Service, Urbana, Illinois; runoff and soil-loss measured from ten plots of grasses and general farming land, each 1/300 acre in size; grazing studies.

INDIANA

LaFayette: Indiana State Agricultural Experiment Station; 1940; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; runoff measured from 20 watershed-units of cultivated, woodland, and pasture-lands ranging in size from 1.7 to 3.5 acres; rainfall measured at eight recording and five non-recording gages; observations also made of air-temperature, soil-moisture, soil-freezing, snow-cover, and soil-moisture. Observations of soil-loss, suspended load, and chemical quality to be started soon.

IOWA

Clarinda: Missouri Valley Loess Region Conservation Experiment Station; November, 1931; address inquiries to Project Supervisor, Soil Conservation Service, Post Office Box 341, Clarinda, Iowa, also Hydrologic Division, Soil Conservation Service, Washington, D. C.; runoff and soil-loss measured from five watershed-units of general farming land ranging in size from 2 to 3.2 acres; 23 plots ranging in size from 1/200 to 1/50 acre; 23 terraces ranging in size from one to seven acres, and 24 lysimeters of six square feet each; rainfall measured at 15 recording and 33 non-recording gages; measurements also made of soil-moisture. Six-year report published.

Iowa City: Ralston Creek Area; September, 1924; address inquiries to Professor J. W. Howe, State University of Iowa, Iowa City, Iowa; runoff (published) measured from one watershed unit of timber, pasture, and agricultural land, 1,925 acres; rainfall measured at five recording and five non-recording gages; observations also made of ground-water levels.

KANSAS

Elkhart: Land Utilization Project; June, 1939; address inquiries to Project Supervisor, Soil Conservation Service, Elkhart, Kansas; observations made of soil-moisture, grass-root penetration, and emergence and survival of grass-plants; rainfall measured at one recording gage and also measurements are made of humidity, air-temperature, air-pressure, and wind-velocities.

Garden City: Garden City Branch, Kansas Agricultural Experiment Station; July, 1939; address inquiries to Project Supervisor, Soil Conservation Service, Garden City, Kansas; rainfall measured at one recording and one non-recording gage; observations also made of soil-moisture and soil-loss under conditions of dryland farming.

Hays: Fort Hays Kansas Agricultural Experiment Station; July, 1929; address inquiries to Project Supervisor, Soil Conservation Service, Hays, Kansas; land-use--general farming and grazing; runoff and soil-loss measured from 11 plots ranging in size from 0.005 acre to 1.61 acres; rainfall measured at one recording and two non-recording gages; observations also made of air-temperature, wind-velocities and evaporation, soil-moisture, contour-furrowing, and effects of grazing.

Manhattan: Agronomy Farm, Kansas Agricultural Experiment Station; July, 1938; address inquiries to Project Supervisor, Soil Conservation Service, Manhattan, Kansas; land-use--general crops and fallow; observations made at 36 lysimeters, 1.8 square feet each; observations also made of air-temperature, evaporation, soil-temperature, and soil-moisture.

LOUISIANA

Baton Rouge: Perkins Road Experimental Farm, Louisiana Agricultural Experiment Station; May, 1938; address inquiries to Project Supervisor, Soil Conservation Service, Louisiana State University, University, Louisiana; land-use--general farming; runoff measured from 27 plots, each 1/13 acre; rainfall measured at one recording and one non-recording gage; observations also made of soil-loss.

MAINE

Ft. Fairfield and Presque Isle: Northern Maine Agricultural Experiment Station; October, 1938; address inquiries to Project Supervisor, Soil Conservation Service, Post Office Box 871, Presque Isle, Maine; land-use--potatoes, hay, and grain; runoff and soil-loss measured from 13 runoff-plots each 1/50 acre; rainfall measured at one recording and two non-recording gages; observations also made of air-temperature, soil-freezing, snow-cover, and soil-moisture.

MARYLAND

College Park: Plant Research Farm of the University of Maryland Agricultural Experiment Station; August, 1939; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; land-use--general farming, truck, pasture, and woodland; runoff measured from nine watershed-units ranging in size from 3 to 15 acres; rainfall measured at five recording and five non-recording gages; observations also made of air-temperature, relative humidity, wind-movement, soil-temperature, soil-freezing, snow-cover, soil-moisture, soil-loss. For information later than June, 1940, concerning air-temperature, soil-temperature, and soil-moisture, address inquiries to Project Supervisor, Soil Conservation Service, Research Laboratory, College Park, Maryland.

Boonsboro: Hagerstown Soil Conservation Service Demonstration Area; March, 1938; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; land-use--orchard and general farming; runoff measured from five watershed-units of which two are terraced, ranging in size from 4.3 to 72 acres; rainfall measured at eight recording and eight non-recording gages; observations also made of air-temperature, relative humidity, and soil-temperature.

MICHIGAN

East Lansing: Michigan Agricultural Experiment Station; 1941; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; land-use--crop- and forest-lands; runoff measured from three watershed-units of two acres; rainfall measured at two recording

MICHIGAN--Concluded

gages; observations also made of air-temperature, wind-movement, evaporation, soil-temperature, soil-freezing, snow-cover, soil-moisture, soil-loss, suspended load, and chemical quality.

MISSISSIPPI

Holly Springs: Holly Springs (Chewalla) Work Center; September, 1931; address inquiries to Director, Southern Forest Experiment Station, United States Forest Service, Federal Office Building, New Orleans, Louisiana; land-use--forest, pasture, and abandoned agriculture land; runoff measured from seven watershed-units ranging in size from 1.32 to 4.23 acres and 42 plots (published) ranging in size from 0.0008 to 0.153 acre; rainfall measured at two recording and 28 non-recording gages; observations also made of air-temperature, soil-temperature, ground-water levels, soil-moisture, and soil-loss.

State College: Mississippi Agricultural Experiment Station; May, 1938; address inquiries to Project Supervisor, Soil Conservation Service, Mississippi Agricultural Experiment Station, State College, Mississippi; land-use--general farming; runoff and soil-loss measured from ten plots, 1/40 acre each; rainfall measured at two recording gages; observations also made of soil-moisture.

Vicksburg: Hydrological Research Project, United States Waterways Experiment Station; September, 1939; address inquiries to United States Waterways Experiment Station, Box 80, Vicksburg, Mississippi; land-use--25 per cent cultivated, 25 per cent woodland, 50 per cent pasture-land; area 3,520 acres; runoff measured from six watershed-units ranging in size from 91 to 1,620 acres; rainfall measured at five recording and 32 non-recording gages; observations also made of air-temperature, wind-movement, evaporation, ground-water levels, sedimentation-surveys, and chemical quality.

MISSOURI

Bethany: Established 1930; address inquiries to Project Supervisor, Soil Conservation Service, 317 Mumford Hall, Columbia, Missouri, also Hydrologic Division, Soil Conservation Service, Washington, D. C.; land-use--general farming and grazing; area--300 acres; runoff measured from seven watershed-units ranging in size from 2.1 to 8 acres; 30 runoff-plots ranging in size from 0.01 to 0.34 acre, and nine terraces ranging in size from 0.6 acre to 2.5 acres; rainfall measured at nine recording and 23 non-recording gages; observations also made of air-temperature, soil-moisture, and soil-loss. Six-year report published.

McCredie: Midwest Claypan Soils Area; 1938; area--300 acres; address inquiries to Project Supervisor, Soil Conservation Service, 317 Mumford Hall, Columbia, Missouri; land-use--grazing and general farming; runoff measured at 41 plots of 1/50 acre each; rainfall measured at one recording and seven non-recording gages; effects of grazing.

MONTANA

Culbertson: Demonstration Project, Montana Agricultural Experiment Station; 1939; address inquiries to Project Supervisor, Soil Conservation Service, Bozeman, Montana; land-use--grazing; rainfall measured at nine recording and six non-recording gages; observations also made of air-temperature, wind-movement, and soil-moisture.

NEBRASKA

Hastings: Central Great Plains Experimental Watershed; 1937; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; land-use--single- and mixed-cover agricultural land; area--3,500 acres; runoff measured from 28 watershed-units ranging in size from 3.4 to 3,490 acres and eight plots, 0.69 acre; rainfall measured at 15 recording and 28 non-recording gages; observations also made of air-temperature, wind-movement, evaporation, soil-temperature, soil-freezing, snow-cover, and soil-moisture.

North Platte, Alliance, and Lincoln: Nebraska Agricultural Experiment Station; 1938; address inquiries to Project Supervisor, Soil Conservation Service, Lincoln, Nebraska; 28 acres of grazing and general farming land; runoff measured from plots 7 feet by 35 feet at temporary locations; rainfall measured at three recording and four non-recording gages; observations also made of soil-moisture, soil-loss, and effect of straw-mulches, incorporation of plant-residues with the soil and type of tillage. Published.

NEW HAMPSHIRE

Durham: New Hampshire Agricultural Experiment Station; February, 1940; address inquiries to Project Supervisor, Soil Conservation Service, Durham, New Hampshire; land-use--general farming; runoff and soil-loss measured from seven plots, 1/50 acre each; rainfall measured at four recording and four non-recording gages.

NEW JERSEY

Beemerville: North Jersey Branch Experiment Station; September, 1937; address inquiries to Project Supervisor, Soil Conservation Service, New Jersey Agricultural Experiment Station, New Brunswick, New Jersey; land-use--dairy farming; runoff and soil-loss measured from 10 plots, 0.02 acre each; rainfall measured at 14 recording (includes Marlboro) and 16 non-recording gages; contour-tillage, silage-croping, and organic-matter incorporations with the soil. Published.

NEW JERSEY--Concluded

Freehold: Soil Conservation Service Demonstration Area; February, 1938; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; land-use--truck, potatoes, and general farming with one 17.5-acre watershed terraced; runoff measured from four watershed units ranging in size from 17.5 to 102.7 acres; rainfall measured at seven recording and seven non-recording gages; observations also made of air-temperature, relative humidity, wind-movement, and soil-temperature.

Marlboro: New Jersey Soil Erosion Research Station; June, 1938; address inquiries to Project Supervisor, Soil Conservation Service, New Jersey Agricultural Experiment Station, New Brunswick, New Jersey; land-use--intensified farming; runoff and soil-loss measured from 24 plots ranging in size from 0.015 to 0.03 acre; rainfall measured at (see Beemerville); observations also made of soil-temperature, soil-moisture, effect of organic-matter treatments of the soil.

NEW MEXICO

Albuquerque: Soil Conservation Service Demonstration Area; June, 1939; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; range-land use; runoff measured from three watershed-units ranging in size from 41 to 183 acres; rainfall measured at five recording and five non-recording gages; observations also made of air-temperature, relative humidity, and soil-temperature.

Gallup: Navajo Experiment Station; 1938; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; area--21,000 acres; land-use--range and sparse timber land; runoff and suspended load measured from eight watershed-units ranging in size from 200 to 21,000 acres; rainfall measured at 79 recording rain-gages.

Mexican Springs: Navajo Indian Reservation; 1934; address inquiries to Project Supervisor, Soil Conservation Service, Mexican Springs, New Mexico; land-use--grazing; rainfall measured at 82 recording, 121 non-recording, and 415 semi-standard non-recording gages; observations made of soil-moisture, suspended load, and also 396 lysimeters, each three square feet.

Santa Fe: Soil Conservation Service Demonstration Area; June, 1939; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; range-land use; runoff measured at three watershed-units ranging in size from 52 to 790 acres; rainfall measured at seven recording and seven non-recording gages; observations also made of air-temperature, and relative humidity.

NEW YORK

China (near Deposit): Cold Spring Brook (tributary to West Branch Delaware River); November, 1935; address inquiries to District Engineer, United States Geological Survey, Post Office Box 948, Albany, New York; area--1,020 acres; land-use--State-owned hardwood and softwood plantations; runoff (published) measured from one watershed-unit of 1,020 acres; rainfall measured at one recording (published) and one non-recording gage; observations also made of air-temperature, snow-cover, and ground-water levels.

Cohocton: Soil Conservation Service Demonstration Area; June, 1936; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; land-use--mixed crops; runoff measured from four watershed-units ranging in size from 13.8 to 2,215 acres; rainfall measured at seven recording and seven non-recording gages; observations also made of air-temperature, relative humidity, wind-movement, soil-temperature, snow-cover, and groundwater levels.

East Homer: East Homer Creek (tributary to East Branch Tioughnioga River); October, 1938; address inquiries to District Engineer, United States Geological Survey, Post Office Box 948, Albany, New York; area--4,530 acres of farms and hardwood forests; runoff (published) measured from one drainage-basin, size 4,530 acres; rainfall measured at one recording (published) and one non-recording gage; observations also made of air-temperature, snow-cover (published), and ground-water levels.

Geneva: New York State (Geneva) Agricultural Experiment Station; 1937; address inquiries to Project Supervisor, Soil Conservation Service, University of Maryland, College Park, Maryland; land-use--orchards and dairying; runoff and soil-loss measured from eight plots, 0.01 acre each; rainfall measured at two recording and two non-recording gages.

Hammondsport: Finger Lakes Vineyard Area; 1936; address inquiries to Project Supervisor, Soil Conservation Service, Bailey Hall, Ithaca, New York; land-use--vineyards for grapes; runoff measured from four plots, 1/4 acre each; observations also made of soil-moisture and soil-loss. Measurements of rainfall made (see Ithaca).

Ithaca: Arnot Forest Experiment Station; July, 1934; address inquiries to Project Supervisor, Soil Conservation Service, Bailey Hall, Ithaca, New York; land-use--general farming and grazing; runoff measured from 26 plots ranging in size from 0.005 to 0.15 acre; rainfall measured at 17 recording (including Hammondsport) and 32 non-recording gages; observations also made of soil-temperature, air-temperature, humidity, wind-movement, sunshine, evaporation, snow-cover, soil-moisture, air-pressure, soil-water levels, and soil-loss; also address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.;

NEW YORK--Concluded

land-use--woodland and abandoned farms; 1940; runoff measured from six watershed-units ranging in size from 9 to 18 acres; rainfall measured at five recording gages; observations made of air-temperature, wind-movement, evaporation, soil-temperature, soil-freezing, and snow-cover.

Marcellus: Upper Finger Lakes Region; 1938; address inquiries to Project Supervisor, Soil Conservation Service, Bailey Hall, Ithaca, New York; land-use--dairying; runoff and soil-loss measured from 31 plots ranging in size from 0.005 to 0.02 acre; rainfall measured at six recording and 32 non-recording gages.

South New Berlin: Sage Brook (tributary to Unadilla River); 1932; address inquiries to District Engineer, United States Geological Survey, Post Office Box 948, Albany, New York; 450 acres State-owned hardwood and softwood plantations; runoff (published) measured from one watershed unit of 450 acres; rainfall measured at one recording (published) and one non-recording gage; observations also made of air-temperature, snow-cover (published), and ground-water levels.

Truxton: Shackham Brook (tributary to East Branch of Tioughnioga River); November, 1932; address inquiries to District Engineer, United States Geological Survey, Post Office Box 948, Albany, New York; 2,000 acres largely State-owned hardwood and softwood plantations; runoff (published) from one watershed-unit of 2,000 acres; rainfall measured at two recording (published) gages; observations also made of air-temperature, wind-movement, evaporation, soil-temperature, snow-cover (published), and ground-water levels.

NORTH CAROLINA

Asheville: Bent Creek Experimental Forest; July, 1927; address inquiries to Director, Appalachian Forest Experiment Station, United States Forest Service, Federal Building, Asheville, North Carolina; land-use--abandoned agriculture land, old field-pastures, pine and hardwood forest; area--5,900 acres; runoff measured from eight watershed-units ranging in size from 11 to 774 acres and ten plots, each 64 square feet; rainfall measured at 31 non-recording gages and one recording gage; observations also made of air-temperature, wind-movement, soil-temperature, and soil-loss.

Franklin: Coweeta Experimental Forest; March, 1934; address inquiries to Director, Appalachian Forest Experiment Station, United States Forest Service, Federal Building, Asheville, North Carolina; plant-cover--Appalachian hardwood forest; area--4,300 acres; runoff measured from 26 watershed-units ranging in size from 4 to 4,000 acres; rainfall measured at six recording and 63 non-recording gages; observations also made of air-temperature, wind-movement, ground-water levels, and suspended load.

Raleigh: Bright Tobacco Producing Region; 1939; address inquiries to Project Supervisor, Soil Conservation Service, Raleigh, North Carolina; land-use--tobacco and pastures; runoff measured from 23 plots, each 1/20 acre, and 16 terraces; rainfall measured at one recording and one non-recording gage; measurements also made of air-temperature and soil-loss.

NORTH DAKOTA

Bottineau and Park River: Bottineau and Park River; June, 1940; address inquiries to Project Supervisor, Soil Conservation Service, Fargo, North Dakota; land-use--wheat-fallow; observations made of soil-moisture, effect of contour-furrows in pasture and incorporation of straw-residues with the soil.

OHIO

Coshocton: North Appalachian Experimental Watershed; 1935; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; area--31,300 acres of single- and mixed-cover agricultural land; runoff measured from 46 watershed-units ranging in size from 0.82 acre to 31,300 acres and 9 lysimeters, each 87.1 square feet; rainfall measured at 41 recording and 64 non-recording gages; observations also made of air-temperature, wind-movement, evaporation, soil-temperature, soil-freezing, snow-cover, ground-water levels, soil-moisture, soil-loss, and chemical quality.

Hamilton: Soil Conservation Service Demonstration Area; May, 1938; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; land-use--cultivated farmland part of which is terraced; runoff measured from four watershed-units ranging in size from 16.2 to 186.6 acres; rainfall measured at six recording and six non-recording gages; observations also made of air-temperature, relative humidity, and soil-temperature. (Observations discontinued in 1940.)

Zanesville: Northwest Appalachian Experiment Station; 1932; address inquiries to Project Supervisor, Soil Conservation Service, Box 208, Zanesville, Ohio, also Hydrologic Division, Soil Conservation Service, Washington, D. C.; area--250 acres of grazing and general farming land; runoff measured from nine watershed-units ranging in size from 0.5 acre to 3.6 acres; 15 runoff-plots ranging in size from 0.005 to 0.02 acre, and 20 terraces ranging in size from 0.4 acre to 1.9 acres; rainfall measured at 19 recording and 42 non-recording gages; observations also made of soil-loss. Five-year report published.

OKLAHOMA

Cherokee: Wheat-land Conservation Experiment Station; July, 1939; address inquiries to Project Supervisor, Soil Conservation Service, Box 465, Guthrie, Oklahoma; runoff measured from nine watershed-units ranging in size from 1.8 to 8.5 acres; 24 plots ranging in size from 3/4 acre to 4 acres, and 24 terraces ranging in size from 3/4 acre to 4 acres; observations also made of precipitation (see Guthrie), air-temperature, evaporation, and soil-moisture.

Guthrie: Red Plains Conservation Experiment Station; 1929; address inquiries to Project Supervisor, Soil Conservation Service, Box 465, Guthrie, Oklahoma, also Hydrologic Division, Soil Conservation Service, Washington, D. C.; area--270 acres of general farming land; runoff measured from nine watershed-units ranging in size from 2.5 to 33.4 acres and 17 plots ranging in size from 0.005 acre to 1 acre; rainfall-observations made at 31 recording (includes Guthrie and Cherokee) and 23 non-recording gages; measurements also made of air-temperature, evaporation, and soil-moisture.

Muskogee: Soil Conservation Service Demonstration Project; September, 1938; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; land-use--alfalfa, mixed crops, meadow; runoff measured from four watershed-units ranging in size from 14 to 61.4 acres; precipitation measured at six recording and six non-recording gages; observations also made of air-temperature, relative humidity, and soil-temperature.

OREGON

Moro: Sherman Branch Experiment Station; March, 1938; address inquiries to Project Supervisor, Soil Conservation Service, Pendleton, Oregon; land-use--fallow-wheat; runoff-observations made of six plots of 1/50 acre each; observations also made of air-temperature, soil-temperature, soil-moisture, and effects of straw-mulches, burning of crop-residues, and incorporation of plant-residues with the soil.

Newberg: Soil Conservation Service Demonstration Area; 1938; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; land-use--orchard and woodland; runoff measured from four watershed-units ranging in size from 6.2 to 21.6 acres; rainfall measured at four recording and four non-recording gages; observations also made of air-temperature, relative humidity, and soil-temperature.

Pendleton: Pendleton Field Station; March, 1939; address inquiries to Project Supervisor, Soil Conservation Service, Pendleton, Oregon; land-use--fallow-wheat; observations made of air-temperature, soil-temperature, soil-moisture, and effects of incorporating straw-residues with the soil.

PENNSYLVANIA

State College and Arendtsville: Pennsylvania Agricultural Experiment Station; 1934; address inquiries to Project Supervisor, Soil Conservation Service, Post Office Box 301, State College, Pennsylvania; land-use--general farming, fruit and dairying; runoff measured from 28 plots ranging in size from 1/200 to 1/7 acre; rainfall measured at four recording and 14 non-recording gages; observations also made of soil-moisture and effects of orchard-mulching; published.

PUERTO RICO

Mayaguez and Rio Piedras: Puerto Rico Experiment Station; January, 1938; address inquiries to Project Supervisor, Soil Conservation Service, Mayaguez, Puerto Rico; land-use--general farming; rainfall measured at 20 recording and 25 non-recording gages; observations also made of soil-moisture and soil-loss.

SOUTH CAROLINA

Clemson: Clemson Agricultural Experiment Station; 1936; address inquiries to Project Supervisor, Soil Conservation Service, Box 952, Clemson, South Carolina; land-use--cotton and general farming; runoff and soil-loss measured from 18 plots ranging in size from 0.0025 to 0.01 acre; rainfall measured at six recording and six non-recording gages; observations also made of soil-moisture and the effects of incorporating organic matter with the soil.

Greenville: Enoree River; January, 1939; address inquiries to Sedimentation Division, Soil Conservation Service, Washington, D. C.; land-use--typical Piedmont watershed of woodland and cultivated land, mostly cotton, in about equal amounts; stream-flow measured from one watershed-unit of 64.4 square miles; rainfall measured at ten recording gages; observations also made of air- and stream-temperature, stream-bed surveys, dissolved load, suspended load, bed-load, and turbidity; observations relate mostly to the transportation of suspended load and bed-load and is the only station of its kind in the United States.

SOUTH DAKOTA

Brookings: Great Plains Area; June, 1939; address inquiries to Project Supervisor, Soil Conservation Service, Brookings, North Dakota; land-use--grazing and general farming; rainfall measured at two recording gages; studies and measurements made of wind-movement.

TENNESSEE

Camden: Benton County Area; February, 1941; address inquiries to A. S. Fry, Head Hydraulic Engineer, Tennessee Valley Authority, 705 Union Building, Knoxville, Tennessee; land-use--

TENNESSEE--Concluded

pasture; runoff measured from one 270-acre watershed; rainfall measured at one recording and two non-recording gages; observations also made of ground-water levels, and suspended load including sedimentation-surveys.

Copperhill: Copperhill Work Center; 1935; address inquiries to Director, Appalachian Forest Experiment Station, United States Forest Service, Federal Building, Asheville, North Carolina; land-condition--denuded, grass-land, and hardwood forest; runoff measured from six watershed-units ranging in size from 5 to 89 acres; rainfall measured at six recording and 14 non-recording gages; observations also made of air-temperature, wind-movement, evaporation, soil-temperature, and suspended load.

Ducktown: Copper Basin Nos. 3 and 4; July, 1940 (records previous to July, 1940, collected by Appalachian Forest Experiment Station, United States Forest Service); address inquiries to A. S. Fry, Head Hydraulic Engineer, Tennessee Valley Authority, 705 Union Building, Knoxville, Tennessee; plant-cover Copper Basin No. 3--grass and open ranged, Copper Basin No. 4--grassed, fenced, grazed; runoff measured from one 5.76-acre watershed in Copper Basin No. 3 and one 6.4-acre watershed in Copper Basin No. 4; rainfall measured at one recording rain-gage in each basin.

Isabella: Copper Basin Nos. 5 and 6; July, 1940 (records previous to July, 1940, collected by Appalachian Forest Experiment Station, United States Forest Service); address inquiries to A. S. Fry, Head Hydraulic Engineer, Tennessee Valley Authority, 705 Union Building, Knoxville, Tennessee; plant-cover--both basins denuded; runoff measured from one 15.36-acre watershed in Copper Basin No. 5 and one 4.38-acre watershed in Copper Basin No. 6; rainfall measured at one recording and one non-recording gage in each basin; observations also made of air-temperature, wind-movement, evaporation, and soil-temperature.

Lexington: Henderson County Area; February, 1941; address inquiries to A. S. Fry, Head Hydraulic Engineer, Tennessee Valley Authority, 705 Union Building, Knoxville, Tennessee; land-use--pasture; runoff measured from one 100-acre watershed; rainfall measured at one recording and one non-recording gage; observations also made of ground-water levels and suspended load including sedimentation-surveys.

New Tazewell: Big Barren Creek; October, 1934; address inquiries to A. S. Fry, Head Hydraulic Engineer, Tennessee Valley Authority, 705 Union Building, Knoxville, Tennessee; land-use--mixed agriculture, pasture, and hardwood forest; runoff and suspended load measured from one 14,400-acre watershed; rainfall measured at one recording gage.

Sharps Chapel: White Creek; November, 1934; address inquiries to A. S. Fry, Head Hydraulic Engineer, Tennessee Valley Authority, 705 Union Building, Knoxville, Tennessee; plant-cover--hardwood forest; runoff and suspended load measured from one 1715-acre watershed; rainfall measured at three recording gages.

Sneedville: Big Sycamore Creek; November, 1934; address inquiries to A. S. Fry, Head Hydraulic Engineer, Tennessee Valley Authority, 705 Union Building, Knoxville, Tennessee; land-use--mixed agriculture, pasture, and hardwood forest; runoff and suspended load measured from one 3,522-acre watershed; rainfall measured at one recording and one non-recording gage.

Wales: Giles County Area; February, 1940; address inquiries to A. S. Fry, Head Hydraulic Engineer, Tennessee Valley Authority, 705 Union Building, Knoxville, Tennessee; land-use--pasture; runoff measured from one 100.5-acre watershed; rainfall measured at one recording and one non-recording gage; observations also made of ground-water levels and suspended load including sedimentation-surveys.

TEXAS

Amarillo: Texas Panhandle Region; 1938; address inquiries to Project Supervisor, Soil Conservation Service, Amarillo, Texas; rainfall measured at two recording and 15 non-recording gages; measurements also made of air-temperature, wind-movement, evaporation, soil-moisture, and soil-loss.

Dalhart: Dalhart Dust Bowl; 1936; land-use--grasses, sorghums, and corn; address inquiries to Project Supervisor, Soil Conservation Service, Amarillo, Texas; rainfall measured at one recording and five non-recording gages; studies also made of air-temperature, wind-movement, soil-moisture, soil-loss, and sand-dune elimination.

Mesquite: Garland Soil Conservation Service Demonstration Area; August, 1938; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; land-use--cultivated, meadow, terraced- and strip-cropped; runoff measured from six watershed-units ranging in size from 10.4 to 97 acres; rainfall measured at seven recording and seven non-recording gages; observations made of air-temperature, relative humidity, and soil-temperature.

Spur: Rolling Plains, Texas Agricultural Experiment Substation No. 7; 1928; address inquiries to Superintendent, Soil Conservation Service, Spur, Texas; 400 acres of grazing and cotton land; runoff measured from seven watershed-units ranging in size from five to 12 acres; eight runoff-plots, 1/75 acre each, five terraces, six to nine acres; and 16 (oil-drum)

TEXAS--Concluded

lysimeters; rainfall measured at two recording and three non-recording gages; observations also made of air-temperature, evaporation, soil-moisture, and soil-loss. Thirteen-year report published.

Temple: Blackland Experiment Station; 1929; address inquiries to Project Supervisor, Soil Conservation Service, Box 414, Temple, Texas; area--547 acres of general agriculture lands; runoff measured from two watershed-units of 2.2 acres each, 25 plots ranging in size from 0.005 acre to 1.39 acres, 20 terraces ranging in size from one to four acres, and 12 lysimeters, 6 square feet each; rainfall measured at seven recording and 29 non-recording gages; observations also made of air-temperature, wind-movement, evaporation, soil-temperature, and soil-loss. Seven-year report published.

Tyler: Arkansas-Louisiana-East Texas Sandy Lands; 1930; address inquiries to Project Supervisor, Soil Conservation Service, Route 9, Tyler, Texas; also Hydrologic Division, Soil Conservation Service, Washington, D. C.; area--173 acres general farming lands; runoff measured from three watershed-units ranging in size from 1.7 to 7.9 acres, 23 plots ranging in size from 0.005 to 0.067 acre, 22 terraces ranging from 0.7 acre to 3.6 acres; rainfall measured at nine recording and 11 non-recording gages; measurements also made of soil-loss. Seven-year report published.

Vega: Soil Conservation Service Demonstration Area; March, 1938; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; land-use--wheat- and range-lands; runoff measured from three watershed-units ranging in size from 21.2 to 129.4 acres; rainfall measured at seven recording and seven non-recording gages; observations also made of air-temperature, relative humidity, and soil-temperature.

Waco: Blacklands Experimental Watershed; 1936; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; land-use--single- and mixed-cover agricultural land; runoff measured from 31 watershed-units ranging from 3 to 5,860 acres and four plots of 0.243 acre; rainfall measured at 35 recording and 78 non-recording gages; observations also made of air-temperature, wind-movement, evaporation, soil-temperature, snow-cover, ground-water levels, soil-moisture, soil-loss, suspended load, sedimentation-surveys, and chemical quality.

UTAH

Ephraim: Great Basin Branch Station; 1914; address inquiries to the Director, Intermountain Forest and Range Experiment Station; United States Forest Service, Forest Service Building, Ogden, Utah; plant-cover--herbaceous mountain-range plants; area--5,000 acres; runoff measured from two watershed-units, ten acres each, and six plots, each 0.1 acre; rainfall measured at one recording and ten non-recording gages; observations also made of air-temperature, wind-movement, snow-cover, and soil-loss.

Farmington: Wasatch Forest; 1936; address inquiries to the Director, Intermountain Forest and Range Experiment Station, United States Forest Service, Forest Service Building, Ogden, Utah; plant-cover--brush, forest, and range; area--3,000 acres; runoff measured from eight watershed-units ranging in size from 3 to 7,500 acres, 42 plots ranging in size from 1/200 to 1/40 acre; rainfall measured at four recording and 123 non-recording gages; observations also made of air-temperature, wind-movement, soil-temperature, soil-moisture, snow-cover, and soil-loss.

VIRGINIA

Blacksburg: Virginia Agricultural Experiment Station; 1937; address inquiries to Project Supervisor, Soil Conservation Service, Blacksburg, Virginia; general land-use--pasture; runoff measured from two plots, 1/25 acre each; rainfall measured at seven recording and two non-recording gages; observations also made of soil-moisture and effects of contour-furrowing; also address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; land-use--general farming; April, 1939; runoff measured from three watershed-units ranging in size from 5.44 to 60 acres; precipitation measured at three recording and three non-recording gages; observations also made of air-temperature, relative humidity, soil-temperature, and soil-moisture.

Chatham: Danville Soil Conservation Service Demonstration Area; July, 1938; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; land-use--cultivated or terraced; runoff measured from three watershed-units ranging in size from 13.3 to 17.1 acres; rainfall measured at three recording and three non-recording gages; observations made of air-temperature, relative humidity, soil-temperature.

VERMONT

Burlington: Vermont Agricultural Experiment Station; May, 1940; address inquiries to Project Supervisor, Soil Conservation Service, 590 Main Street, Burlington, Vermont; land-use--pasture, hay, and corn; runoff measured from 13 plots ranging in size from 0.005 to 0.0225 acres; rainfall measured at four non-recording gages; observations also made of soil-freezing, soil-moisture, and soil-loss.

WASHINGTON

Dayton: Dayton Soil Conservation Service Demonstration Area; 1939; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; area--19.2 acres of cultivated land; runoff measured from one watershed-unit, size 19.2 acres; rainfall measured at two recording and two non-recording gages; observations also made of air-temperature, relative humidity, and soil-temperature.

Pullman: Pacific Northwest Area; 1930; address inquiries to Project Supervisor, Soil Conservation Service, Pullman, Washington, also Hydrologic Division, Soil Conservation Service, Washington, D. C.; land-use--wheat-fallow and grass; runoff (published) measured from four watershed-units ranging in size from 14 to 762 acres and 42 plots ranging in size from 0.005 to 0.02 acre; rainfall measured at six recording and 12 non-recording gages; measurements made of soil-moisture and soil-loss. Six-year report published.

WISCONSIN

Fennimore: Soil Conservation Service Demonstration Area; June, 1938; address inquiries to Hydrologic Division, Soil Conservation Service, Washington, D. C.; land-use--cultivated farmland; runoff measured from four watershed-units ranging in size from 22.8 to 330 acres; rainfall measured at nine recording and nine non-recording gages; observations also made of air-temperature, relative humidity, and soil-temperature.

La Crosse: Upper Mississippi Valley Erosion Experiment Station; 1932; address inquiries to Project Supervisor, Soil Conservation Service, Box 667, La Crosse, Wisconsin, or Hydrologic Division, Soil Conservation Service, Washington, D. C.; land-use--general farming; runoff observed at three watershed-units of 2.62 acres each, 60 plots ranging in size from 0.005 to 0.033 acre, four terraces and 12 lysimeters, six square feet each; rainfall measured at nine recording and 19 non-recording gages; observations also made of soil-freezing and soil-loss. Four-year report published; also address inquiries to Director, Lake States Forest Experiment Station, University Farm, St. Paul, Minnesota; plant-cover or land-use--grazed and ungrazed oak-hickory woods and pasture; 1934; runoff measured from three watershed-units ranging in size from 2.67 to 11.50 acres, and ten lysimeters, each 1/200 acre; rainfall measured at one recording and two non-recording gages.

WYOMING

Archer: Eastern Wyoming Great Plains Area; 1938; address inquiries to Project Supervisor, Soil Conservation Service, Agronomy Department, Wyoming University, Laramie, Wyoming; land-use--pasture-land; rainfall observed at two recording gages; observations also made of soil-moisture and effect of contour-furrows.

Washington, D. C.

NOTES ON JOINT ROUND-TABLE ON RUNOFF AND INFILTRATION

NORTH INTERIOR BUILDING, 9:00 A.M., MAY 3, 1941

W. G. Hoyt, Chairman, Committee on Runoff, and
G. W. Musgrave, Chairman, Committee on Infiltration

On Saturday, May 3, 1941, a round-table discussion was held under the auspices of the Section of Hydrology on the questions:

(1) Under what conditions are the relations between infiltration and runoff quite definite and marked?

(2) Under what conditions are the relations between infiltration and runoff partially or largely obscured?

(3) What basic information is needed most urgently to further our ability to predict runoff from known rainfall?

(4) What aspects beyond runoff and infiltration result from snow, ice, frozen ground, and contrasting land-use conditions?

This session was attended by about 100 members of the Section of Hydrology, 70 of whom attended the special luncheon at one o'clock which followed the round-table. The attendance included an excellent representation from various Federal agencies interested in hydrologic problems, including the Soil Conservation Service, the Geological Survey, the Forest Service, the Weather Bureau, the Engineer Department, as well as representatives from political subdivisions and utilities companies.

Following introductory remarks by the Chairmen, short statements were made by W. C. LOWDERMILK, President-elect of the American Geophysical Union, and N. C. GROVER, President of the Section of Hydrology.

Questions (1) and (2), being closely associated, were discussed as one topic. The question of definitions for infiltration-capacity, infiltration-rate, infiltration-index, and average loss-rate was raised. After considerable discussion it was agreed that these terms would be defined by the speakers in order to avoid confusion. It was felt impractical at this time to arrive at definitions for these terms that would be generally acceptable. It was clearly evident from the discussions, however, that there is a real need for a set of definitions relating to the phenomenon of infiltration which can be generally agreed upon. The discussion turned to questions which arose in connection with the paper presented at the regular session, namely, "Separating storm-hydrographs from small watersheds into surface- and subsurface-flow" by C. R. Hursh and E. F. Brater, which was used as an example to illustrate the phenomena of subsurface storm-flow, ground-water or base-flow, effect of pressure on ground-water flow, ground-water slopes, soil-porosity, and infiltration. Additional discussion concerned the determination of outflow at a gage from basic infiltration-data, drainage-density, storage, unit-hydrographs, and inflow-hydrographs.

The observations of various persons with regard to the behavior of base-flow and the possibilities under which base-flow may be suddenly increased with the occurrence of rainfall were also discussed in this connection.

The deduction from this discussion is that the relations between infiltration and stream-flow may be definite and marked or partially or largely obscured depending upon the characteristics of the drainage-basin under consideration.

On one extreme are areas with very high infiltration-capacity and small storage-capacities and on the other are those basins with low infiltration-capacities and large storage-capacities.

Discussion turned toward the paper presented by O. E. Guthe and J. C. Owen at the Friday morning session on the subject of "A proposed method for calculating stream-flow" by a determination of moisture-losses to the air through evaporation and transpiration, the amount and distribution of four-hour increments of rainfall, and the changes in natural storage. The net residue available to valley-storage was computed and then the four-hour values of stream-discharge.

Although the results were not perfect, the method is in part a new approach and worthy of further investigation. At the present time, it was brought out, the procedure involves the amassing of a large quantity of rainfall and land-use data and doing a good deal of analytical work in the way of computation, which possibly may be cut down. Certain difficulties that may be in the path of the ultimate accomplishment of objectives of the paper were pointed out.

In a discussion of question (3) the needs for basic information to apply scientific hydrologic data to practical engineering problems were presented by those engaged in design and operation of reservoirs, flood-forecasting, and the determination of the effects of land-use on runoff. Additional basic data needed pertains to infiltration-capacities, physical watershed-characteristics such as drainage-density and soil-cover complexes, time-distribution of rainfall, soil-moisture data, smaller time-increments in rainfall-intensity, stream-flow records, increased accuracy in reporting total rainfall at standard gages, more stream-flow records from smaller tributaries, stream-flow records transmitted to a central office during the course of a storm, and finally, correlation between new precipitation-gages and the surrounding older gages and correlation between observation of runoff at experimental areas and observation of runoff from drainage-basins of significant size.

It was brought out that the needs of the various agencies and organizations for rainfall-data vary widely and that for flood-control operation purposes a six-hour or 12-hour period of breakdown precipitation is about all that can be handled with sufficient expedition. Such records are also frequently adequate for the design and operation of downstream structures, but on the Department of Agriculture's flood-control program, which concerns especially the land-use and management-phase, records for periods of an hour or less down to five minutes are desirable.

In the discussion of question (4) it was pointed out that in Pennsylvania and New York all winter hydrographs show at least some ground-water recharge. In a discussion of the effect of frozen ground the following was presented as factual information: (1) That ground frozen when relatively dry (about ten per cent) often has a higher porosity than similar ground frozen when wet (20 to 30 per cent); (2) that frozen ground thaws under a blanket of snow 18 to 24 inches deep; (3) that under a one-meter snow-blanket the surface soil-temperature varies only a fraction of a degree from 0°C; and (4) that the freezing temperature of soil is below that of water, being approximately 27°F. There was a discussion of the phenomena of needle-ice formation in soils. The opinion was expressed that this is a capillary effect and results in partially drying the surface-soil.

A vote of thanks was extended to N. C. GROVER, President of the Section of Hydrology of the American Geophysical Union, and R. A. HERTZLER, Chairman of the Program Committee of the Section of Hydrology, for their work in arranging and conducting the meeting this year, which was felt to be a success.

Discussion was opened relative to the matter of the many papers and the crowded schedule at the regular meetings of the Section of Hydrology. It was felt that either fewer papers should be presented or that the period of the meeting should extend over a longer succession of days, with the general trend of thought being toward the idea of fewer papers with more opportunity for formal and informal discussion. There seemed to be a concensus that the round-tables should continue. It was felt that the Program Committee now has the proper authority to regulate the length of the program as seems best.

Round-table adjourned at 1 p.m. for lunch.

U. S. Geological Survey,
U. S. Soil Conservation Service,
Washington, D. C.

REPORT OF RESEARCH-COMMITTEE OF EASTERN SNOW-CONFERENCE

G. A. Hathaway, Carroll F. Merriam (Chairman), and J. Sweet

The principal effort of the Research-Committee of the Eastern Snow-Conference has been to stimulate thought regarding the amount of heat necessary to melt snow-cover. Melting snow obviously holds a part of the portion already melted in suspension by capillary attraction and, therefore, the true latent heat of the mass as a whole is the product of 80 calories per gram times the percentage of the total that has not been melted. This latter may be called the thermal quality of snow, corresponding to the term used in thermodynamics known as the "quality" of steam.

It is of particular interest to know whether this quality can become sufficiently reduced under field-conditions, so that it will indicate potential danger of floods resulting from warm rain falling on the partly melted cover. So far practically no investigations had been made of this kind.

Although the work was begun rather late to carry out any systematic survey in the field, some effort was made to explore the technique and to study the sources of error, the methods of correcting them, and to lay down in general the principles of good experimental procedure to meet a variety of conditions. A number of experiments were carried out under the direction of Merrill Bernard in the Weather Bureau, and some cooperation was secured from other laboratories. As a result three memoranda were circulated among the members of the Eastern Snow-Conference and others known to be interested in snow-surveys throughout the country. These notes discussed the difficulties encountered and how they were overcome, the general limitations to accuracy, methods of sampling, etc.

There is need of much more comprehensive work, and it is expected that in the course of a few months reports will come from some of the men who are already making systematic observations for the Weather Bureau in the West. A number of educational institutions, particularly in the Northeast, have expressed willingness to assign this subject for students' theses for the coming year. A number of Government agencies have shown interest and have offered to cooperate to the extent that they can.

The apparatus required is not expensive, and it has been shown that the technique is not too difficult for any observer possessing reasonable skill and willingness to observe certain simple precautions.

Whether or not it will prove practical to supplement snow-surveys with measurements of this kind is problematic. It does seem, however, within the range of probability that with experience a good observer will be able to develop a sense of feel which will enable him to judge the approach of dangerously low thermal quality by the appearance and consistency of the snow-mass. So far all tests have been limited unfortunately to rather coarse-grained snow, and the results have not shown as wide a variation in quality as might have been expected. The Committee desires reports from as wide a range of conditions as possible so that it may be judged whether or not this reduction in latent heat is a factor which contributes to the production of destructive floods.

INDEX OF NAMES, PART III, 1941

T. C. Adams, 916
R. E. Allen, 649
Clark Amens, 972
David L. Arenberg, 962
J. T. Auten, 908

R. W. Bailey, 908
Henry I. Baldwin, 955, 964
H. K. Barrows, 908
H. P. Barss, 963
C. G. Bates, 908
Robert E. Bates, 905
Paul L. Bean, 955, 958, 961
M. E. Beatty, 1009
William A. Beck, 926
Frank T. Been, 1010
Aurelio Benassini, 1014
Merrill Bernard, 944, 955, 957, 963, 976, 1014
Colin Bertram, 964
Harry F. Blaney, 909, 941, 948
H. P. Boardman, 972
E. F. Brater, 863
J. Harlen Bretz, 952
C. Frank Brockman, 1007
Charles F. Brooks, 961, 966, 969, 977
S. C. Brooks, 926
Bolton Coit Brown, 970
Walter E. Brown, 964
G. M. Brune, 649
Ralph W. Burhoe, 981

J. J. Capello, 587
David W. Cardwell, 856
J. E. Church, 953
Phil E. Church, 793, 954, 956, 960, 962
F. E. Clements, 909
Harold H. Clum, 927
A. L. Cochran, 726
Russell S. Colley, 968
William T. Collins, 854
R. C. Collison, 909
E. A. Colman, 909
Harold Conkling, 910, 962
C. K. Cooperrider, 910
John S. Cotton, 911
R. H. Cotton, 927
Philip S. Cowgill, 970
A. S. Crafts, 927
Irving B. Crosby, 904
W. P. Cross, 949
E. S. Cullings, 976

J. M. Davidson, 1014
W. E. Davis, 906
Max Demorest, 791, 965
W. E. Dickerson, Jr., 856
C. H. Diebold, 678, 795
H. G. Dorsey, Jr., 961, 979
S. B. Doten, 965
F. L. Duley, 911
James L. Dyson, 1009

N. E. Edlefsen, 694, 917, 938
H. A. Einstein, 597
Carl Elges, 970, 981
E. B. Escott, 667
H. C. Eyster, 929

William O. Field, Jr., 796
J. A. Fleming, 587
W. L. S. Fleming, 964
L. J. Foster, 963
S. H. Frame, 956

Willard Gardner, 929, 948
B. R. Gilcrest, 637
H. T. Gisborne, 964
R. S. Goodridge, 862, 902
G. A. Greathouse, 929
H. R. Gregg, 1010
N. C. Grover, 1027, 1028
E. J. Gumbel, 836, 850
O. E. Guthe, 799
W. F. Guyton, 744, 756

L. C. Halpenny, 738
S. O. Harper, 958
Arthur W. Harrington, 955
G. A. Hathaway, 942, 1014, 1029
B. A. Hendricks, 911
W. C. Hendrix, 587
R. A. Hertzler, 1028
Walter Herz, 977
G. H. Hickox, 911
H. O. Hill, 911
Eric Hinton, 954
William H. Hobbs, 965
Benjamin Holzman, 655
O. H. Hoover, 955
Robert E. Horton, 696, 811, 820, 930, 1012
C. S. Howard, 901, 903
George W. Howard, 636
W. G. Hoyt, 870, 954, 1014, 1027
M. King Hubbert, 770
Martin R. Huberty, 686, 931
N. D. Hudson, 688, 694
C. R. Hursh, 863

L. Jacchia, 981
C. E. Jacob, 744, 783
C. S. Jarvis, 621, 843, 875
J. W. Johnson, 607
Walter B. Jones, 951
A. R. Jordan, 931

Benjamin C. Kadel, 979
A. A. Kalinske, 603, 620
T. A. Kiesselbach, 911
Koreo Kinosita, 968
Joseph Kittredge, 906, 963
Helmut Kohnke, 912
P. J. Kramer, 931
Masawo Kuroda, 968

A. C. Lane, 597
E. W. Lane, 603, 905
W. A. Lang, 971
W. B. Langbein, 897, 941

Donald B. Lawrence, 1008
Fred F. Lawrence, 1006
J. Otis Laws, 709
C. H. Lee, 912
A. D. Lewis, 602
George A. Lewis, 954
M. R. Lewis, 931, 942
R. K. Linsley, 722
B. E. Livingston, 932
W. F. Loehwing, 932
S. W. Lohman, 772
W. E. Loomis, 933
H. J. Loughead, 912
S. K. Love, 949
W. C. Lowdermilk, 1027
H. J. Lutz, 912

L. E. Marsh, 637
Francois E. Matthes, 1006
G. H. Matthes, 622, 624, 632, 904
L. C. Mayer, 666
Leo M. Mayfield, 978
Alexander G. McAdie, 969
W. T. McFarlane, 955
James McIver, Jr., 966
W. W. McLaughlin, 964
O. E. Meinzer, 744
Carroll F. Merriam, 703, 707, 959, 1029
A. F. Meyer, 912
E. Meyer-Peter, 965
Charles W. Miller, 958
E. C. Miller, 933
N. E. Minshall, 871
B. C. Moneymaker, 951
O. W. Monson, 933
José Garcia Montes, 697, 941
Arthur M. Morgan, 779
John Muir, 970
E. N. Munns, 913, 948
H. C. Murto, 875
G. W. Musgrave, 721, 809, 913, 934, 941, 1014, 1027

Ukitiro Nakaya, 977
O. R. Neal, 913
Frank Neighbor, 952
M. L. Nichols, 934, 1013
C. H. Niederhof, 660

J. C. Owen, 799

G. G. Parker, 949
Ralph L. Parshall, 955
Walter J. Parsons, Jr., 959
G. J. Peirce, 934
J. E. Phillips, 979
Kenneth N. Phillips, 1008
Arthur F. Pillsbury, 686
A. M. Piper, 913
E. R. Pohl, 952
Ralph W. Powell, 849
W. Armstrong Price, 952
William Pruitt, Jr., 962

Andrés García Quintero, 726

C. E. Ramser, 948
R. W. Revell, 906
Roger Revelle, 593
Roger F. Rhoades, 951
L. A. Richards, 913
H. S. Riesbol, 946
Brian Roberts, 964
Bestor Robinson, 966, 972
Hilda F. Rosene, 934
H. E. Rothrock, 951
P. B. Rowe, 913
W. W. Rubey, 620, 630
J. H. Ryan, 957

Thorndike Saville, 849
W. E. Scott, 587
Hugh A. Shamberger, 959
H. L. Shantz, 934
B. T. Shaw, 935
L. K. Sherman, 666, 697, 960
Samuel Shulits, 622, 631
Frederick H. Sibley, 979
I. H. Sims, 1014
A. D. Singer, 587
Arthur L. Smith, 978
Edward H. Smith, 788, 964
G. E. P. Smith, 955, 961
Waldo E. Smith, 851
H. I. Snider, 966
F. F. Snyder, 808, 893
J. C. Stevens, 602
H. Stoltenberg, 977
Lorenz G. Straub, 901, 903, 905
John B. Sweeney, 968
J. Sweet, 1029
A. C. Swinnerton, 783, 950

C. V. Theis, 734
Herbert C. S. Thom, 659, 708
H. E. Thomas, 775
David G. Thompson, 948
Thomas Toyn, 978
William Toyn, 978
R. W. Trullinger, 960, 963, 978
E. L. Tullis, 952
S. F. Turner, 738
M. C. Tyler, 904

Vito A. Vanoni, 608
F. J. Veihmeyer, 914, 935

Warren O. Wagner, 977
Herbert A. Waite, 772
D. S. Wallace, 949
E. F. Wallihan, 914
R. D. Waterhouse, 977
J. E. Weaver, 914
C. A. Wellner, 964
F. W. Went, 936
L. K. Wenzel, 737
P. R. White, 936
W. N. White, 744
Karl J. Wilkinson, 978
H. G. Wilm, 660, 678, 914, 1014
Floyd Wilson, 1010
Walter T. Wilson, 893
C. O. Wisler, 866
R. A. Work, 793, 956, 957, 960, 969, 977

A. A. Young, 914

INDEX OF SUBJECTS, PART III, 1941

- Agricultural engineers engaged in hydrologic work, 946
- Airport-drainage, relation of infiltration to the problem of, 942
- Alaskan glaciers, gazetteer of, 796
- American Society of Agricultural Engineers and American Geophysical Union, report of Coordinating Committee on Hydrology, 946
- Application of coefficients of transmissibility and storage to regional problems in the Houston District, Texas, 756
- Application of the infiltration-theory to engineering practice, 666
- Artesian storage, computations of inflow and withdrawal from, Houston District, Texas, 766
- Autogiro, use of in snow-fields, 972
- Avalanches, 967

- Baffin Bay and Davis Strait, cruise in 1940, Coast Guard Cutter Northland, 788
  - Iceberg-distribution in, 789
- Basic aspects of stream-meanders, 632

- Camera, drop-velocity, 710
- Channel-inflow, virtual, graphs, 811
- Channel-storage
  - Determination of, by use of virtual-inflow graphs, 813
  - Flood-crest reduction by, 820
- Channel-storage and discharge-relations in the lower Ohio River Valley, 637
- Chemistry of Natural Waters, report of Committee on, 901
- Coast Guard Cutter Northland's ice and oceanographic observation cruise, Baffin Bay and Davis Strait, autumn of 1940, 788
- Coefficients of storage and transmissibility obtained from pumping tests in the Houston District, Texas, 744
- Committee-reports
  - Advisory on Soil Conservation Research, 1012
  - Coordinating on Hydrology, American Society of Agricultural Engineers and American Geophysical Union, 946
  - Chemistry of Natural Waters, 901
  - Dynamics of Streams, 903
  - Eastern Snow-Conference, 974
  - Evaporation and Transpiration, 906
  - Flood-Waves, 901
  - Glaciers, 1006
  - Land-Forms, 904
  - Physical limnology, 916
  - Physics of Soil-Moisture, 917
  - Rainfall, 944
  - Runoff, 1014
  - Snow, 953
  - Underground Waters, 948
- Consideration of factors influencing reservoir-sedimentation in the Ohio River Region, 649
- Considerations on an index to measure effective rainfall, 697
- Criteria for recognition of sea water in groundwaters, 593
- Cumberland River
  - Hydrograph for 1939 flood at Smithland, Kentucky, 647
  - Storage for steady flow, 645

- Dams, ground-water, created by faulting of alluvial sediments in the Hurricane Fault-Zone, Utah, 775
- Davis Strait and Baffin Bay
  - Cruise of Coast Guard Cutter Northland in 1940, 788
  - Iceberg-distribution in, 789
- De-icing plane-wings, 968
- Depth of active solution by ground-waters in the Pecos Valley, New Mexico, 779
- Discharge-relations, and channel-storage, in the lower Ohio River Valley, 637
- Distribution-coefficients, instantaneous, versus period, 851
- Drainage-areas, separating storm-hydrographs from small, into surface- and subsurface-flow, 863
- Drainage-basins, estimating annual yield from ungaged, 875
- Drop-velocity camera, 710
- Dynamics of Streams, report of Committee on, 903

- Earthquakes, fluctuations of water-level caused by, 949
- Eastern Snow-Conference
  - Committees of, 974
  - Report of Research-Committee of, 1029
- Effect of a well on the flow of a nearby stream, 734
- Elasticity of Lloyd sand, Long Island, New York, 783
- Energy, free
  - Changes of natural processes, 921
  - Of water, negative character of in unsaturated soils and in solution, 922
  - Relation between changes in and work performed in reversible and irreversible processes, 920
  - Space-rate of change of, 922
  - Thermodynamic properties of, 918
- Engineering calculations of suspended sediment, 603
- Estimating annual yield from ungaged drainage-basins and effect of land-use treatment on surface-runoff, 875
- Evaporation and Transpiration, report of Committee on, 906
- Evaporation from water-surfaces, heat-balance method for determination of, 655
- Experiments on the transportation of suspended load, 608
- Extending the forecasts of temperature for the prediction of stream-flow from snow-melt, 722

- Factors influencing infiltration-rates into some California soils, 686
- Factors producing a nine-year decline in groundwater levels in Scott County, Kansas, 772

Fall-velocity of water-drops and raindrops, measurements of, 709
Faulting of alluvial sediments, ground-water dams created by in Hurricane Fault-Zone, Utah, 775
F-curves, diagram for derivation of, from loss-rates, 668
Fennimore, Wisconsin, preliminary results of runoff-studies at, 871
Fertilizers and soluable salts, effect of on the rate of absorption of irrigation-water by the soil, 686
Flood-crest reduction by channel-storage, 820
Flood-frequency, 836
Flood-recurrence intervals, limitations of the duration-interval concept of, 862
Flood-routing, example, Missouri River, 895
Flood-routing method, graphical, 893
Floods
  Effect of snow in producing, 959
  Probability-interpretation of the observed return-periods of, 836
  Runoff from terraced areas under conditions of extreme, 856
Flood-Waves, report of Special Committee on, 901
Forest-fires, relation of scant snow-cover to increase in, 964
Free energy, thermodynamic properties of, 918

Gazetteer of Alaskan glaciers, 796
Gila River Valley, New Mexico and Arizona, ground-water inventory; scope of investigation and methods used, 738
Glaciers
  Alaskan, gazetteer of, 796
  Report of Committee on, 1006
Glaze- and rime-measurement, Mount Washington Observatory, 962
Graphical flood-routing method, 893
Ground-water dams created by faulting of alluvial sediments in the Hurricane Fault-Zone, Utah, 775
Ground-water inventory in the upper Gila River Valley, New Mexico and Arizona: Scope of investigation and methods used, 738
Ground-water levels, in Scott County, Kansas, factors producing a nine-year decline in, 772
Ground-waters
  Criteria for recognition of sea water in, 593
  Depth of active solution by, in the Pecos Valley, New Mexico, 779

Heat-balance method for the determination of evaporation from water-surfaces, 655
Houston District, Texas
  Application of coefficients of transmissibility and storage to regional problems in, 756
  Coefficients of storage and transmissibility obtained from pumping tests in, 744
  Computation of inflow and withdrawal from artesian storage from, 766
Hurricane Fault-Zone, ground-water dams created by faulting alluvial deposits in, 775
Hydrograph-synthesis, 897
Hydrologic research-data being collected at experimental areas, watersheds, forests, and demonstration-projects maintained by Federal agencies (Appendix A), 1016
Hydrologic research-projects, 944
Hydrology
  Papers, 593
  Reports of permanent-research committees of, 901
  Research on, and physiography of limestone terranes (Appendix A), 950
Hydrometeorology of the San Juan River Basin, Mexico, 726
Hydrometeorological Service, operation of, 728

Ice and oceanographic observation cruise, of U. S. Coast Guard cutter Northland, Baffin Bay and Davis Strait, autumn of 1940, 788
Ice and snow, list of current publications on (Appendix A), 981
Ice-crusts and snow-settling, Snoqualmie Pass, winter of 1940-41, 793
Iceberg-distribution, map of, in Baffin Bay, Davis Strait, and West Greenland coastal waters, September 5 to 23, 1940, 789
Index to measure effective rainfall, considerations on, 697
Infiltration
  Methods for measurement of, 678
  Plots, 679
  Rates, factors influencing, into some California soils, 686
  Relation of, to problem of airport-drainage, 942
  Report of Committee on, 941
  Variance of, as measured by four methods, 683
Infiltration and runoff, notes on joint round-table, 1027
Infiltration-plots, 679
Infiltration-rates
  Different environmental conditions and different soils, 942
  Factors influencing, into some California soils, 686
Infiltration-theory, application of, to engineering practice, 666
Interception of rainfall by mature lodgepole-pine, 660
Irrigation-waters, effect of fertilizers and soluble salts on the rate of absorption of, by the soil, 686

Land-Forms, report of Sub-Committee on (Appendix A), 904
Land-use treatment, effect of on surface-runoff, 875
Limestone terranes, physiography of, and research on hydrology (Appendix A), 950
Limitations of the duration-interval concept of flood-recurrence intervals, 862
Lloyd sand, notes on the elasticity of, on Long Island, New York, 783
Lodgepole-pine, interception of rainfall by, 660
Long-term constancy of rainfall, 703

Loss-rates, diagram for derivation of f-curves from, 668
Limnology, Physical, report of Committee on, 916

Meanders, stream, pattern of, 634
Measurements of the fall-velocity of water-drops and raindrops, 709
Methods for the measurement of infiltration, 678
Mississippi River
  Derivation of discharge from long-period records, 881
  Hydrograph for 1939 flood at Cairo, Illinois, 641
  Measured and calculated profiles of for 1901, low-water, 628
  Storage for steady flow, 638
  Suspended sediment in, 604
  Variation of low-water slope along, 625
  Velocity-distribution in, at Muscatine, Iowa, 605
Missouri River, flood-routing example, 895
Mount Mansfield, ski-lift at, 967
Mount Washington Observatory, rime- and glaze-measurement, 962

North Central States Snow-Conference, 1940-41, committees of, 975
Notes on the elasticity of the Lloyd sand on Long Island, New York, 783

Oceanographic and ice observation cruise, of U. S. Coast Guard cutter Northland, Baffin Bay and Davis Strait, autumn of 1940, 788
Ohio River
  Channel-storage and discharge-relations in lower valley of, 637
  Factors influencing reservoir-sedimentation in, 649
  Measured and calculated profiles of, 628
  Storage for steady flow, 638
  Variation of low-water slope along, 626
Ohio Valley, consideration of factors influencing reservoir-sedimentation in region of, 649
Ostwald water-viscosimeter, 598

Pecos Valley, New Mexico, depth of active solution by ground-waters in, 779
Period versus instantaneous distribution-coefficients, 851
Phloem of the plant, direction of motion of water in, 924
Physical Limnology, report of Committee on, 916
Physics of Soil-Moisture, report of Committee on, 917
Physiography of limestone terranes and research on hydrology (Appendix A), 950
Plane-wings, de-icing, 968
Plants, phloem of, direction of motion of water in, 924
Polar regions, activities in, 964
Preliminary results of runoff-studies at Fennimore, Wisconsin, show low rates and amounts of runoff, 871
Probability-interpretation of the observed return-periods of floods, 836
Proposed method for calculating stream-flow, 799

Raindrops and water-drops, measurements of the fall-velocity, 709
Rainfall
  Effective, considerations of an index to measure, 697
  Influence of timber-cutting on, 663
  Interception of, by mature lodgepole-pine, 660
  Long-term constancy of, 703
  Mass-departure curves of, 704
  Report of Committee on, 944
Rational equation of river-bed profile, 622
Reports, permanent-research committees of, Section of Hydrology
    First session, 901
    Second session, 917
    Third session, 953
Research committees, permanent, reports of, Section of Hydrology, 901
Reservoir-sedimentation, consideration of factors influencing in Ohio Valley Region, 649
Return-periods of floods, probability-interpretation of observed, 836
Rime- and glaze-measurement, Mount Washington Observatory, 962
River-bed, profile, rational equation of, 622
Runoff, report of Committee on, 1014
Runoff and infiltration, notes on joint round-table, 1027
Runoff from terraced areas under conditions of extreme flood, 856
Runoff-studies, at Fennimore, Wisconsin, 871

San Juan River Basin, Mexico, hydrometeorology of, 726
Scott County, Texas, factors producing a nine-year decline in ground-water levels in, 772
Sea water, criteria for recognition of in ground-waters, 593
Sediment
  Alluvial, ground-water dams created by faulting of, in the Hurricane Fault-Zone, Utah, 775
  Effect on velocity, 614
  Suspended, engineering calculations of, 603
Ski-lift at Mount Mansfield, 967
Ski-lodges, 967
Snoqualmie Pass, ice-crusts and snow-settling, winter of 1940-41, 793
Snow
  Conserving effect of forests on, 963
  Effect of, in producing floods, 959
  Regional reports on, 954
  Report of Committee on, 953
  Transportation over, 965
Snow-cohesion and snow-loads, 969
Snow-conferences, 974
Snow-cover
  Scant, relation of, to increase in forest-fires, 964
  Studies of, 960
Snowfall, annual, relation of, to summer openings of trails in high mountains, 969
Snow-fences, 968
Snow-fields, use of Autogiro in, 972

Snow-loads and snow-cohesion, 969
Snow-melt, prediction of stream-flow from, 722
Snow-motor sleds, 970
Snow-precipitation measurement, 961
Snow-removal, 967
Snow-sampler outfit, 970
Snow-settling and ice-crusts, Snoqualmie Pass, winter of 1940-41, 793
Snow-surveying, 957
Snow and ice, list of current publications on (Appendix A), 981
Soil Conservation Research, report of Advisory Committee on, 1012
Soil-moisture by plants, some thermodynamic aspects of, 917
Soil-Moisture, Physics of, report of Committee on, 917
Some thermodynamic aspects of the use of soil-moisture by plants, 917
Speleological Society of the District of Columbia, 952
Springs of Missouri, report of the Geological Survey of Missouri, 951
Storage and transmissibility, coefficients of obtained from pumping tests in the Houston District, Texas, 744
Storm-hydrographs, separating from small drainage-areas into surface- and subsurface-flow, 863
Stream-flow
  Prediction of, from snow-melt, 722
  Proposed method for calculating, 799
Stream-meanders
  Basic aspects of, 632
  Pattern of, 634
Sublimation, effects of, 961
Sugar-cane crop, approximate standard water-requirements of, 699
Surface-runoff, effect of land-use treatment on, 875
Surface- and subsurface-flow, separating storm-hydrographs from small drainage-areas into, 863
Suspended load
  Closed-circuit flume for studies of, 610
  Determination of, 606
  Distribution of, 611
  Set-up for taking samples of, 611
  Some experiments on the transportation of, 608
Suspended sediment, engineering calculation of, 603

Tallahatchie Basin, derivation of average f-curve, 671
Temperature
  Extending the forecasts of, for the prediction of stream-flow from snow-melt, 722
  Reduction of air-temperature in air passing over snow-fields, 725
Terraced areas, runoff from, under conditions of extreme flood, 856
Thermodynamic aspects of the use of soil-moisture by plants, 917
Thermodynamic properties of free energy, 918
Timber-cutting, influence of on net rainfall to size of storm (gross rainfall), 663
Transpiration and Evaporation, report of Committee on, 906
Transpiration, relation of to different types of vegetation, 801
Tributary records, forecasting monthly and daily discharge from tributary records, 891

Underflows, highly concentrated, viscosity of, and its influence on mixing, 597
Underground Waters, report of Committee on, 948

Virtual channel-inflow graphs, 811
Viscosimeter, Ostwald water-, 598
Viscosity of highly concentrated underflows and its influence on mixing, 597

Wabash River
  Storage for steady flow, 644
Water
  Direction of motion of in the phloem of the plant, 924
  Force causing to move through plants, 924
Water-drops
  Measurements of fall-velocity of, 709
  Velocities of different sizes after various heights of fall, 718
Water-level, fluctuations of caused by earthquakes, 949
Water-levels, observation decline of, in Houston District, Texas, 757
Water-requirements of sugar-cane crop, 699
Water-stage recorder, 739
Watersheds
  Comparison of rainfall and runoff on, 861
  Permanent characteristics of, 860
Water-surfaces, heat-balance method for determination of evaporation from, 655
Western Interstate Snow-Survey Conference, 1940-42, committees of, 975
Wells
  Effect of, on the flow of a nearby stream, 734
  Observation, decline of water-levels in Houston District, Texas, 757